Building a 45 megapixels camera that takes 100,000 pictures per second

Marco Verzocchi – Senior Scientist, Particle Physics Division

Fermilab Ask-a-Scientist

7 January 2016

What am I going to talk about today ?

Between 2013 and 2016 a large group of US scientist has built a new camera for the CMS experiment at the CERN Large Hadron Collider

It was installed in March 2017 and has been operational since then

This is a story of why and how we've built this new camera

I will try to use analogies from our normal lives to make things understandable

A new gem inside the CMS detector

March 23, 2017 | Sarah Charley

Sometimes big questions require big tools. That's why a global community of scientists desig
the high-energy particle collisions generated by CERN's Large Hadron Collider in Geneva, S
can retrace the footsteps of the Big Bang and search for new properties of nature.

The CMS experiment is one such detector. In 2012, it co-discovered the elusive Higgs bosor

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CMS pixel tracker transplant: everything went well so far

by *Achintya Rao*

Posted by Stefania Pandolfi on 13 Mar 2017. Last updated 14 Mar 2017, 15.23.
Voir en français

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Delicate surgery: The new Pixel Tracker being installed at the heart of the CMS detector. (Photo: Max Brice/CERN)

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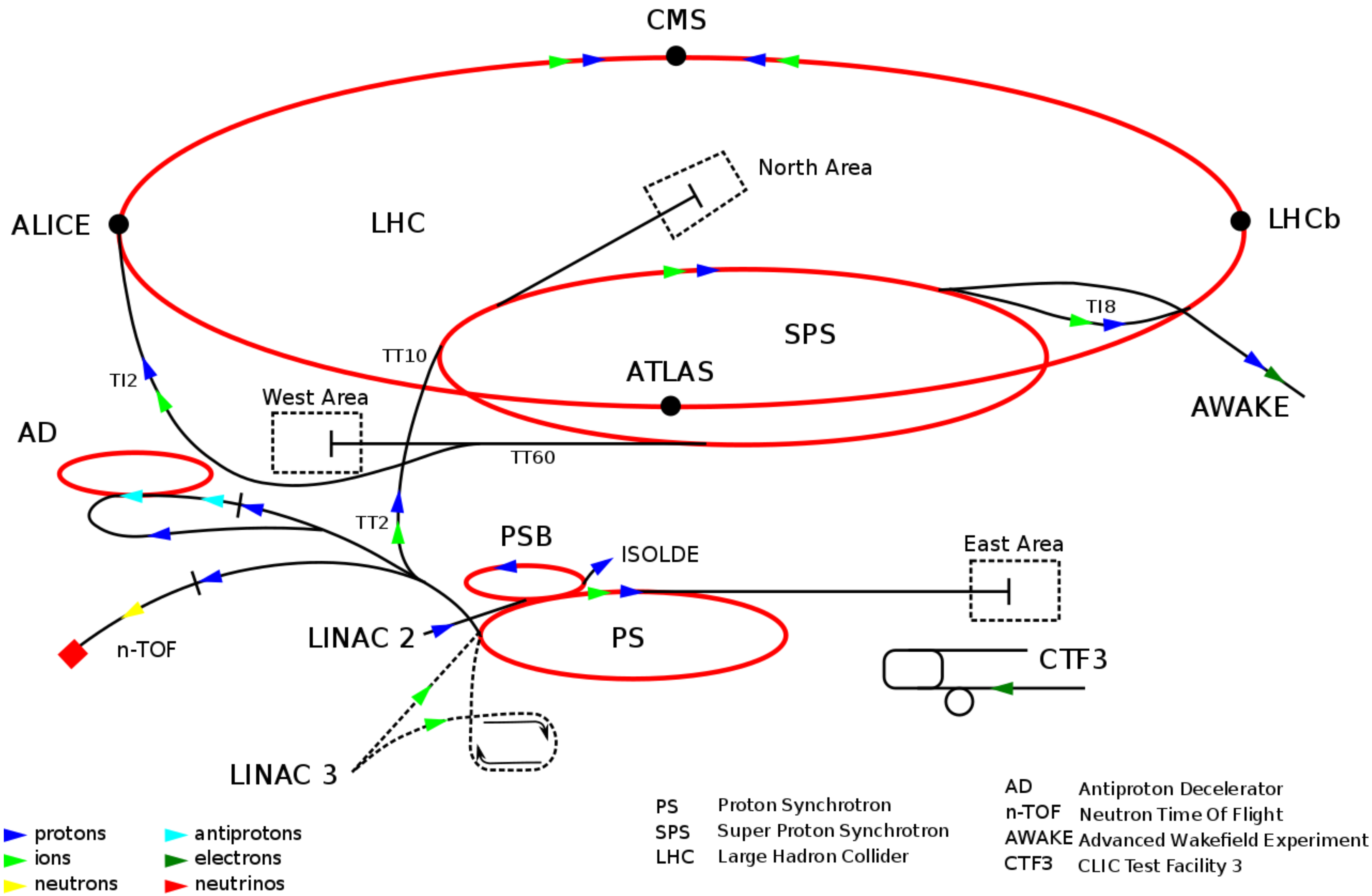
The Large Hadron Collider



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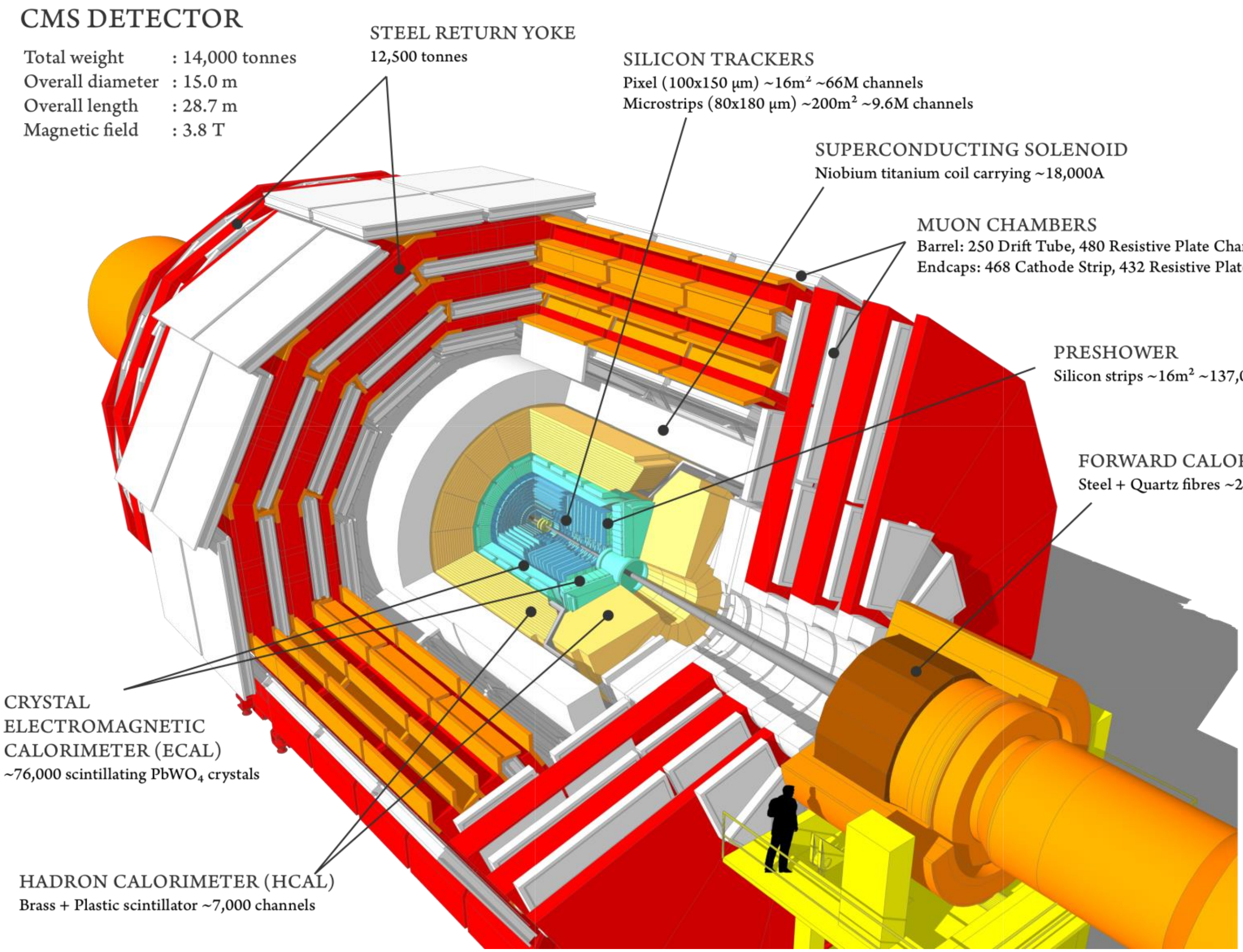
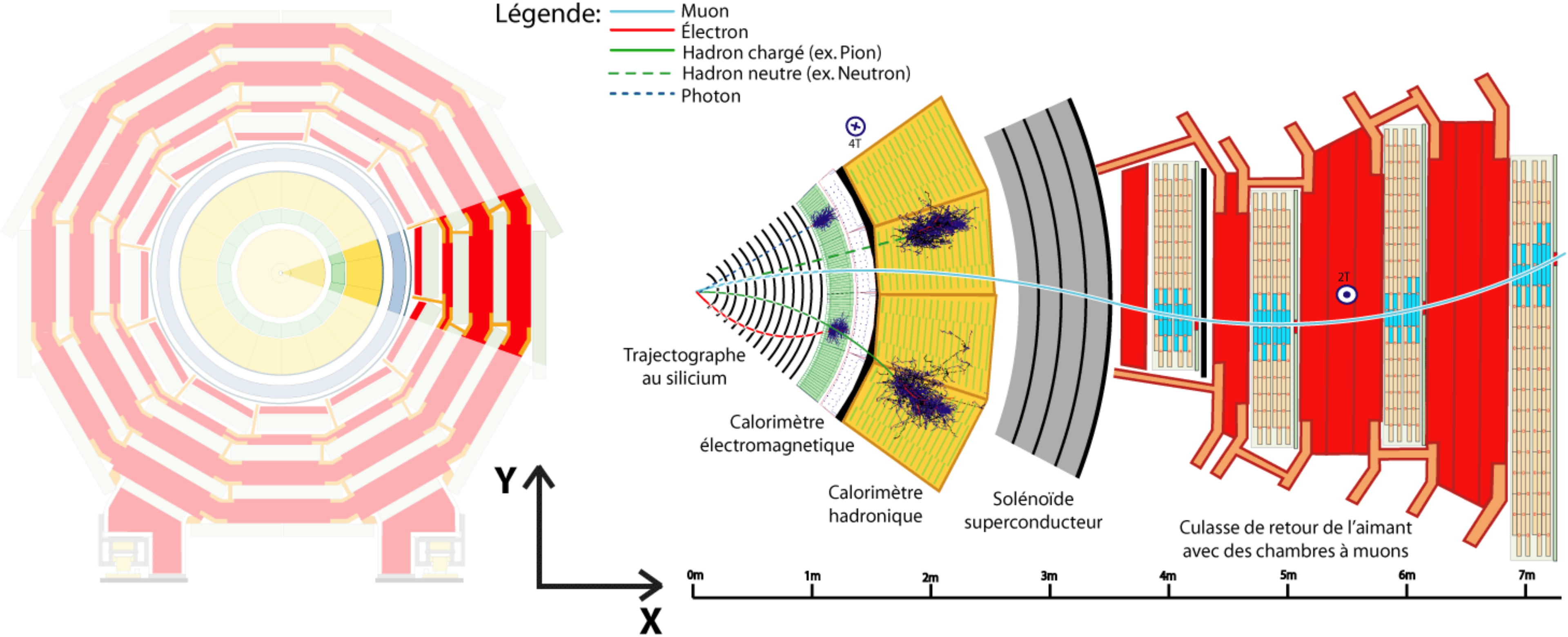
A camera ? Don't you guys use detectors ?



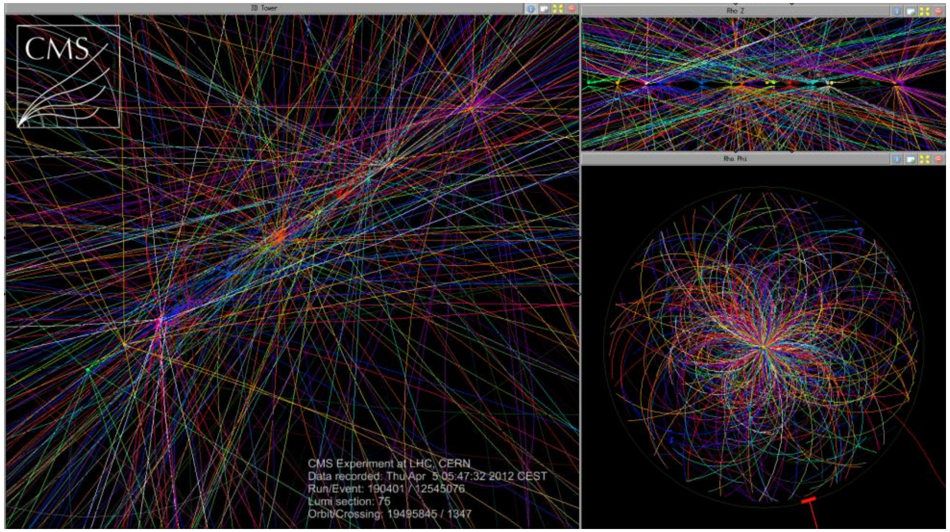
A camera ? Don't you guys use detectors ?

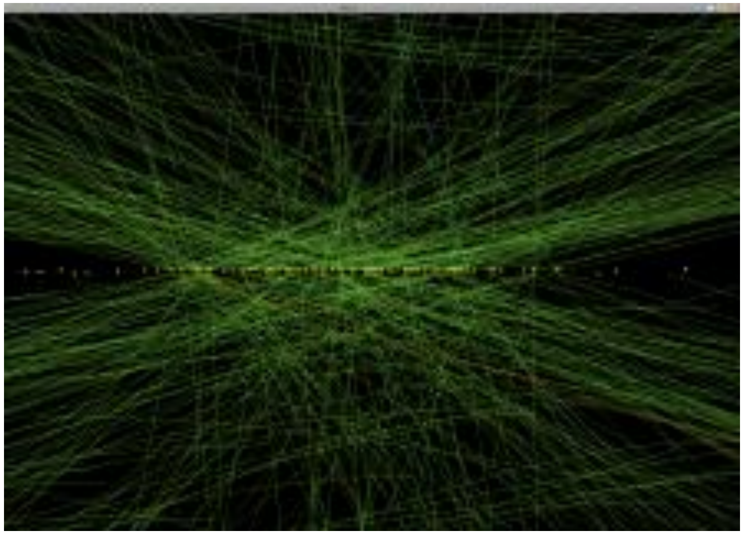


The role of the pixel detector (i)

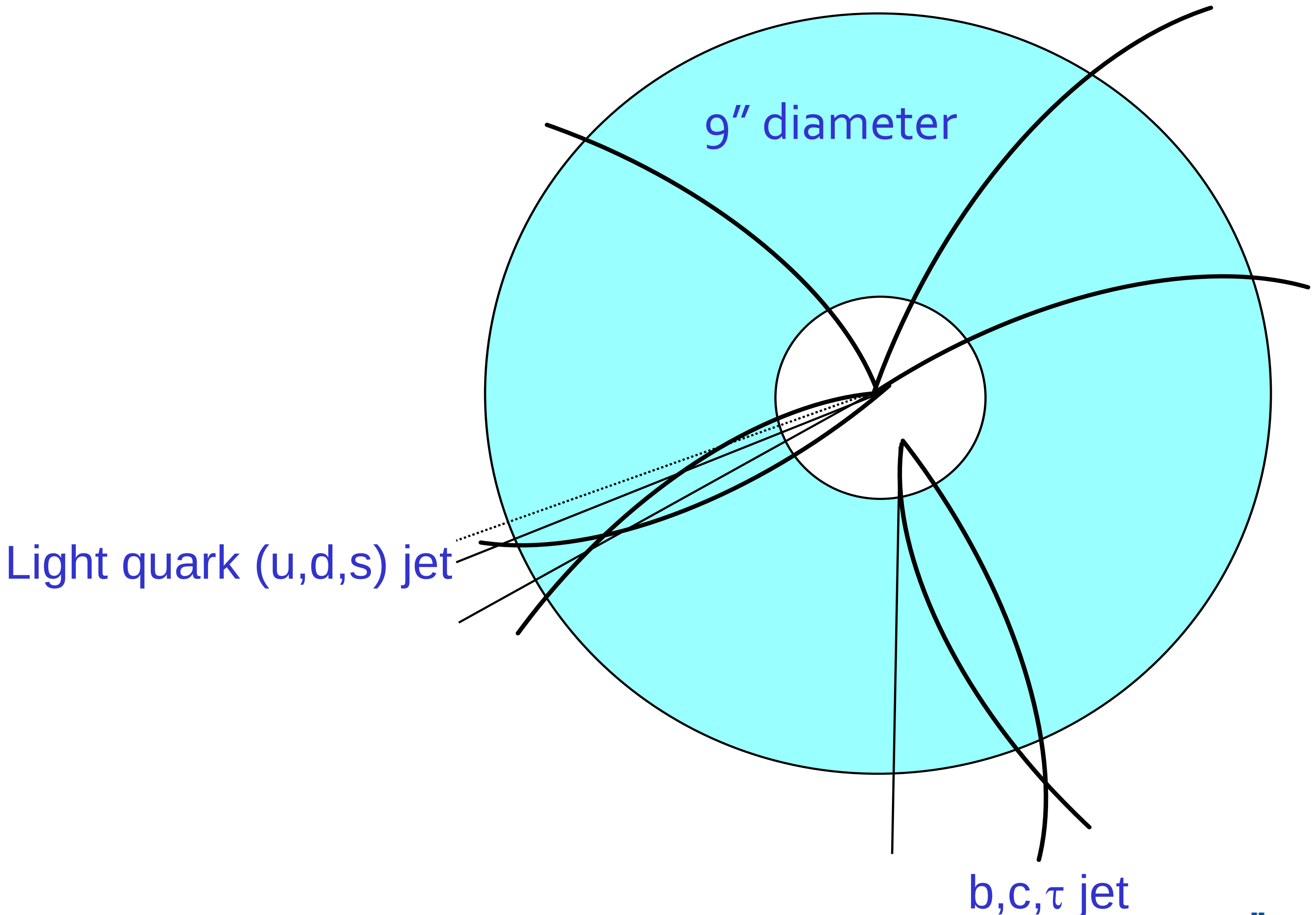
The pixel detector is part of the tracking system:

- Identify the trajectories of charged particles
- Measure their momentum from the bending in the magnetic field
- Reconstruct primary and secondary vertices
- Identify tracks not pointing to a primary vertex





The role of the pixel detector (ii)



Why did we need a new one ? (i)

Just like in a normal household, when the kids discover Snapchat, you need to increase the bandwidth of your internet connection…

Xfinity from Comcast Internet Pricing

Internet Package	Download Speeds Up to	Introductory Price
Performance Starter	10 Mbps	$29.99/mo.*
Performance	25 Mbps	$39.99/mo.*
Performance Pro	100 Mbps	$49.99/mo.*
Blast! Pro	150 Mbps	$59.99/mo.*

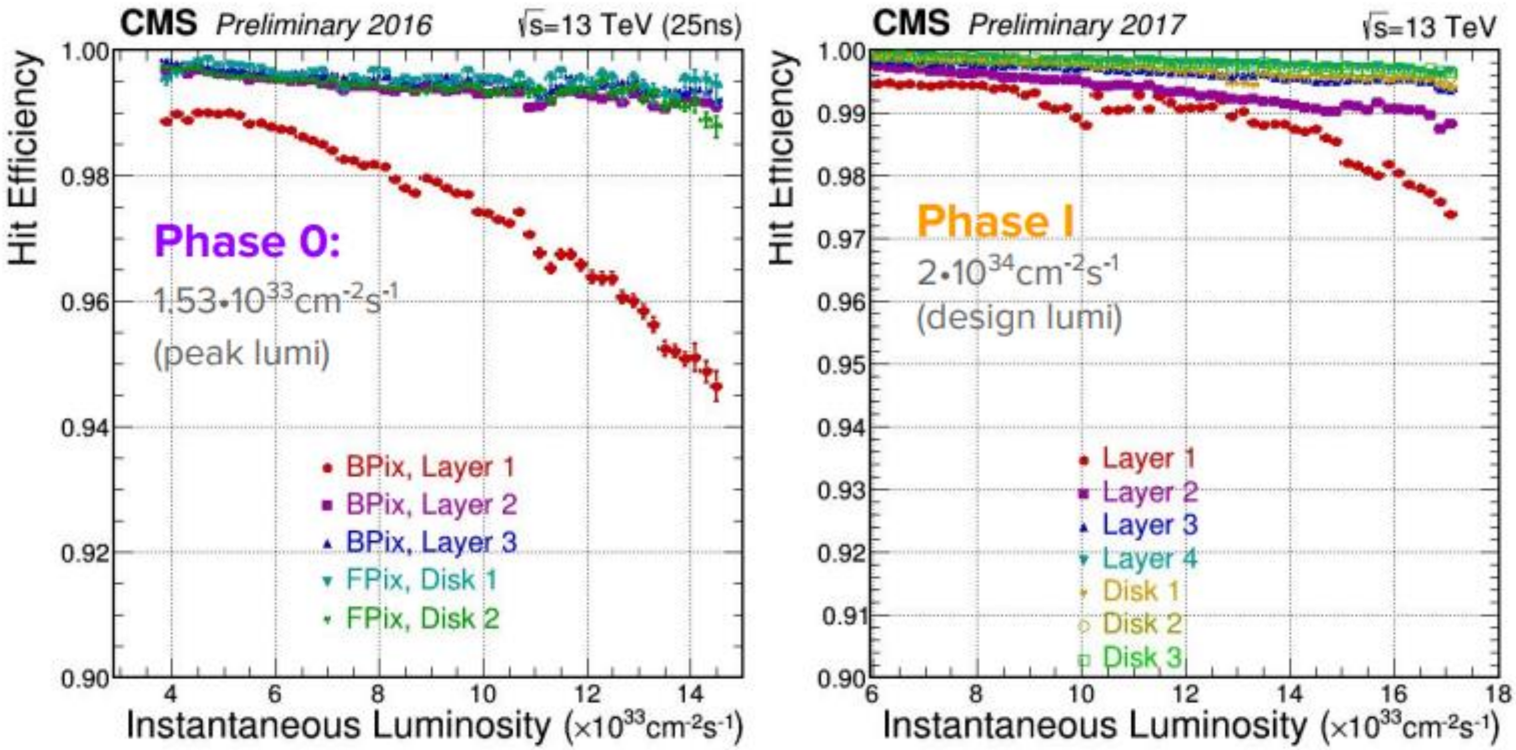
2 more rows

Comcast Internet Plans | XFINITY Internet Prices and Packages
https://www.cabletv.com/xfinity/internet

In the case of CMS:

- kids on Snapchat = events (we’ve got a lot of kids)
- parents complaining = experiment’s boss (we are not collecting data)

Why did we need a new one ? (ii)



The old detector was designed to work at $L=1x10^{34}cm^{-2}s^{-1}$, started being inefficient (loose images) at $L=1.5x10^{34}cm^{-2}s^{-1}$,

New detector can survive up to $L> 2x10^{34}cm^{-2}s^{-1}$

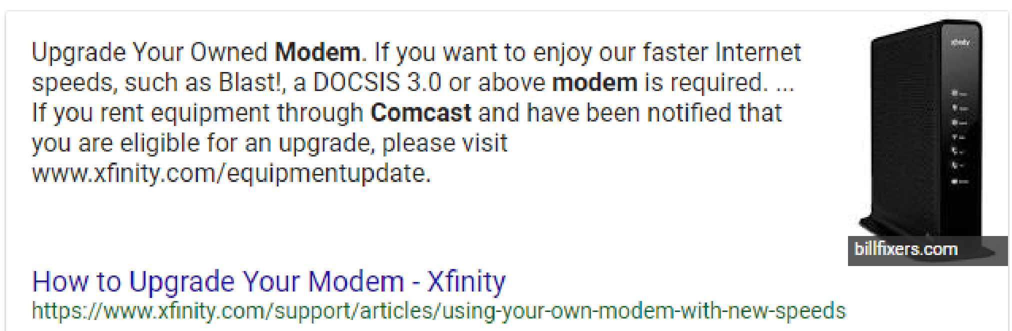
This comes at a cost….

The old detector had 672 modules (households) at 40 Mbps

The new detector has the same number of modules, but they operate at 320 Mbps (8 times faster)

What happens when you ask Comcast to go faster ?

- Your bill increases
- Comcast may want to replace your modem
- Usually they don't change the cable from your house / apartment to some box in the back alley
- You don't know what happens there ……..



In the case of CMS

Replacing the modem

- New data acquisition system (receive ~7 HD movies per second, old system could handle only 1)

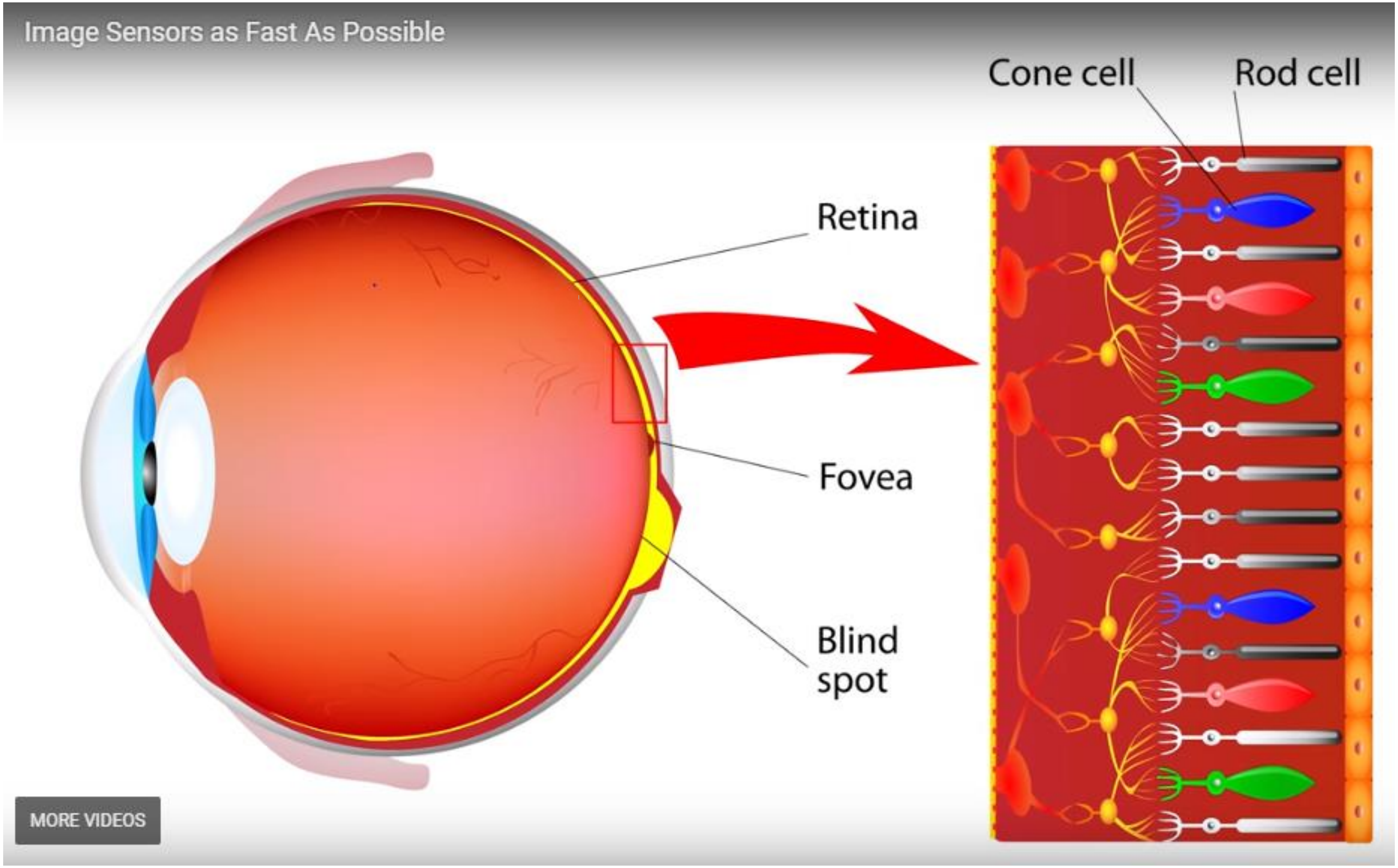
Keep the cable

- In this case they are optical fibers

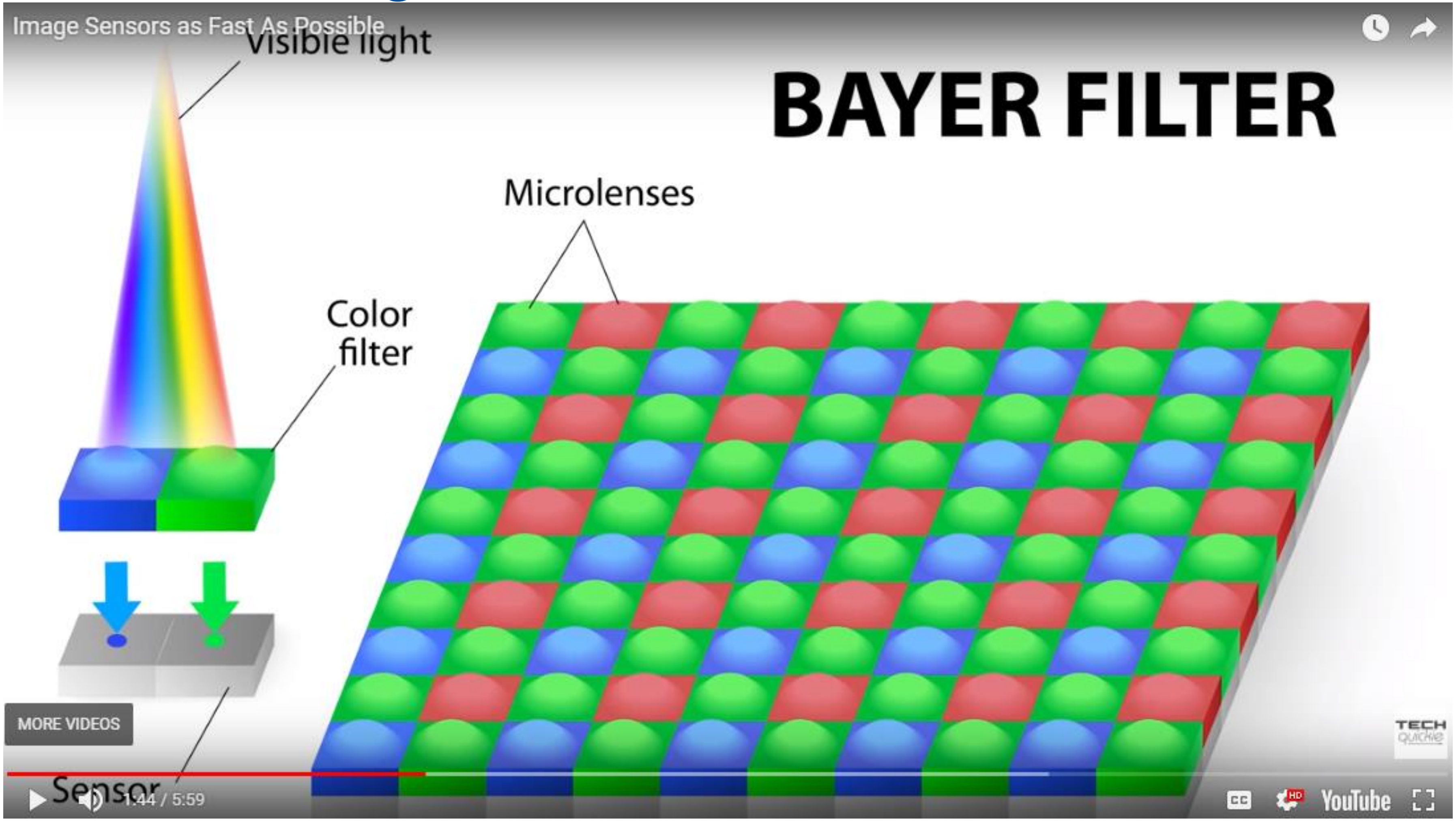
Change the equipment in the back alley

- This is the data source, the chip that translates the signal in the detector into a digital data stream (Netflix on steroids)

How do we see images ?



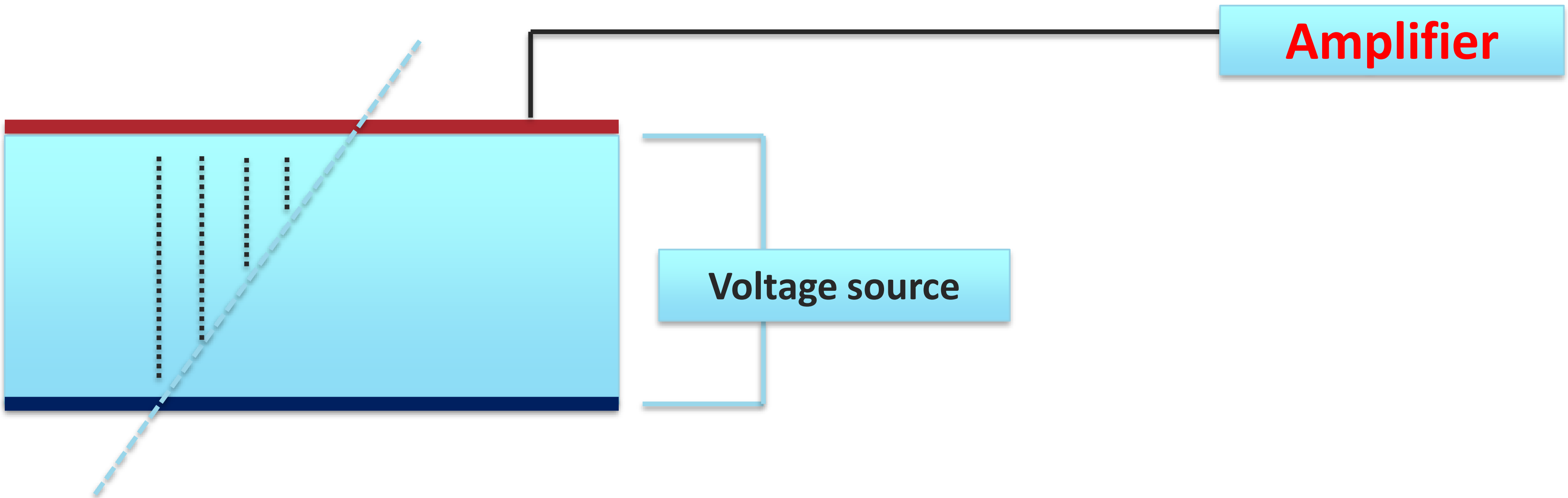
How does a digital camera work ?



https://nofilmschool.com/2015/12/how-hell-do-digital-camera-sensors-actually-work

https://electronics.howstuffworks.com/cameras-photography/digital/question362.htm

How a silicon detector works (1 pixel)



A particle passing through the silicon liberates charges (electrons) that are then collected on an electrode thanks to the external electrical field

If you collect the signal on the electrode and amplify it, you can get a measurement of the energy left by a particle in the silicon (typical charge 24,000 electrons)

Why don't you go online and buy it ?

iPhone X

Video Recording

4K video recording at 24 fps, 30 fps, or 60 fps

1080p HD video recording at 30 fps or 60 fps

720p HD video recording at 30 fps

- 45.7 megapixels of extraordinary resolution, outstanding dynamic range and virtually n
- Up to 9 fps[1] continuous shooting at full resolution with full AF performanc
- 8K[8] and 4K time-lapse movies with new levels of sharpness and detail
- Tilting touchscreen, Focus Shift shooting mode, outstanding battery performance and
- 4K Ultra HD video recording, slow motion up to 120 FPS at 1080p

The ultrahigh-speed FASTCAM SA-Z provides megapixel image resolution at frame rates up to 21,000fps and exceptional light sensitivity (monochrome ISO 50,000) with 12-bit dynamic range delivering the ultimate imaging performance. The FASTCAM SA-Z provides frame rates greater than 2 million fps at reduced image resolution and shutter speeds as short as 159 nanoseconds (export restrictions may apply).

There is nothing on the market that meets our requirements

Why are our silicon detector special ?

LHC beams collide at the center of CMS every 25 ns (40 million times per second)

Each pixel in our detector stores the image for a few µs, until we decide that the image might be interesting (trigger)

At that point the image is transmitted outside of the detector (at a rate of 100,000 images per second)

Differences with normal / fast commercial cameras

- Much higher data transmission rate at full resolution
- Store data locally until trigger decision
- Radiation hardness

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Trigger

LHC beams collide every 40 million times per second

- Multiple proton-proton interactions per bunch crossing

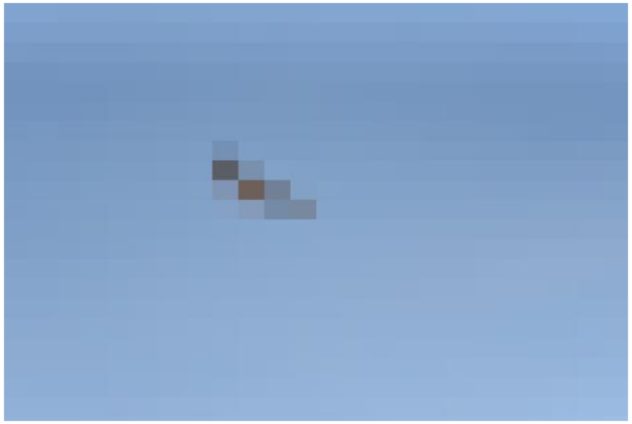
We cannot record all the collisions, storing/processing costs/time would be too large

- Use lower granularity features of event (other detectors, pixel detector not used in this process) to decide which collisions are interesting
- This is the same job as the fashion magazine photo editor choosing the right photograph among the 100s shots of the same model with the same outfit

Trigger example (i)

What do we have in these three pictures ?



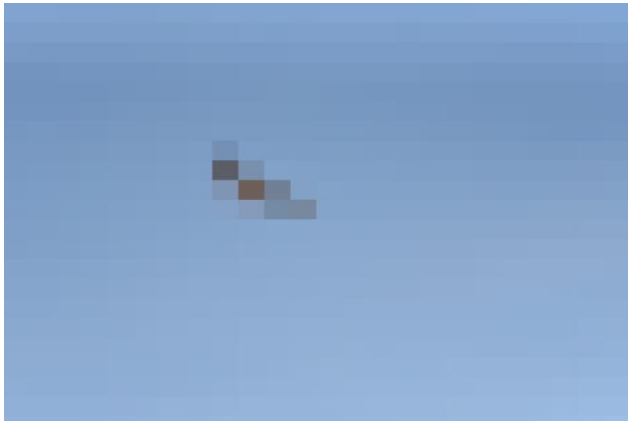


Trigger example (ii)

I took a few thousand pictures last Summer

Here I have a picture of a bird, of an airplane, and bisons

At low resolution can you tell me which is which ?



You know that the picture on the left contains bisons, but only because I told you so, it could be something else…

Let’s increase the resolution …..

Trigger example (iii)

I took a few thousand pictures last Summer

Here I have a picture of a bird, of an airplane, and bisons

At low resolution can you tell me which is which ?

It's pretty obvious which one is the bird and which one is the airplane… but can you recognize the bird ?

Trigger example (iv)

I took a few thousand pictures last Summer

Here I have a picture of a bird, of an airplane, and bisons

At low resolution can you tell me which is which ?



The CMS trigger works exactly in the same way… First you look at low resolution data to distinguish an object in the sky from animals on the ground

Then you increase the resolution and distinguish the bird from the plane

Data analysis

When you have the full resolution, you can see that this is some sort of hawk (I am not a birding expert….)

Radiation Hardness

The central part of the CMS detector sees harsh conditions (up to 200 Mrad, 1 krad is deadly for humans)

Health effects [edit]

Main article: Radiation poisoning

A dose of under 100 rad will typically produce no immediate symptoms other than blo
acute radiation syndrome, (ARS) but is usually not fatal. Doses of 200 to 1,000 rad de
the range. Whole body doses of more than 1,000 rad are almost invariably fatal.[3] Th

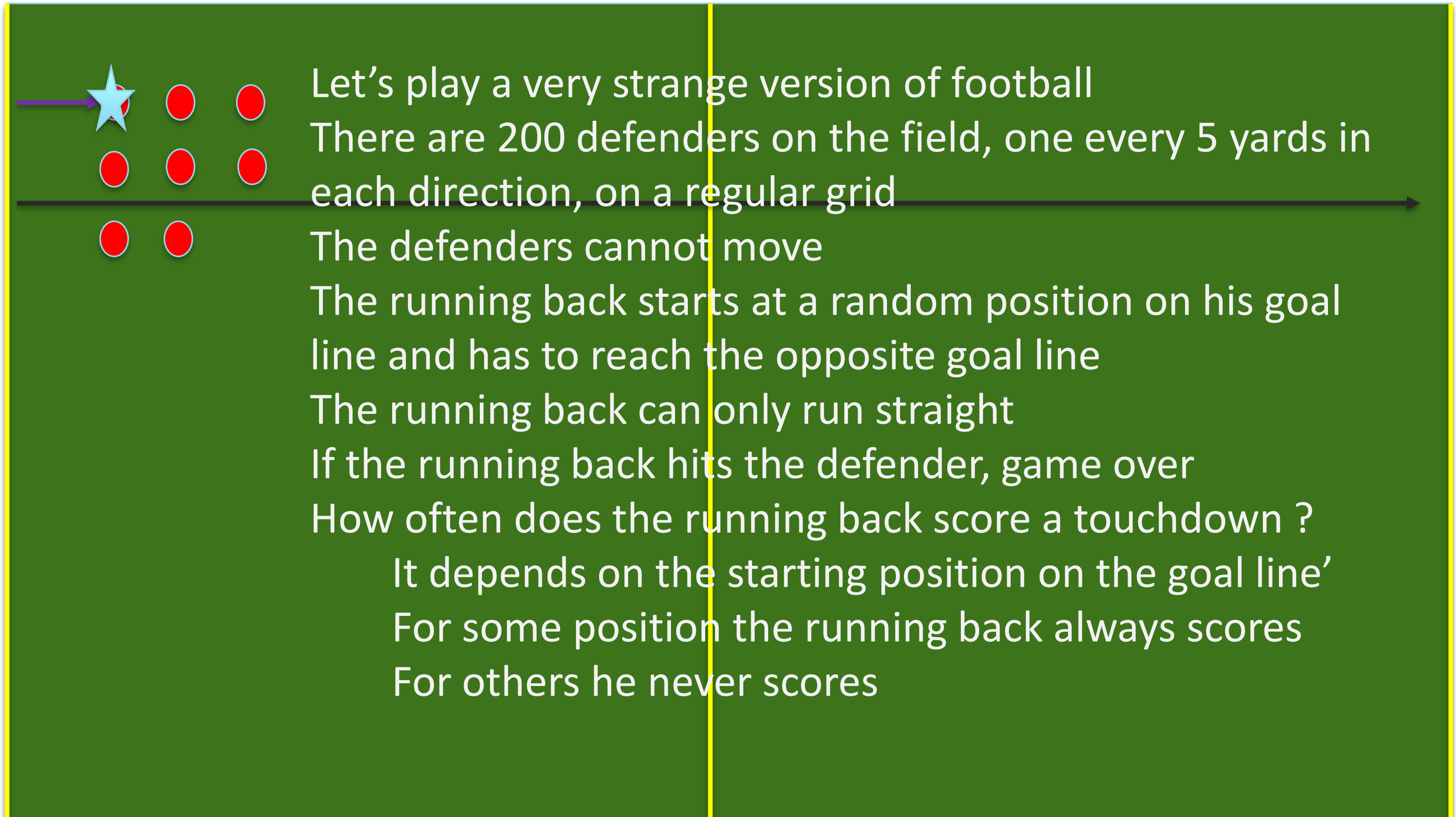
Even electronics can be damaged by radiation (mostly relevant for space satellites and LHC electronics)

Standard consumer electronics will not survive inside the CMS detector

All electronics for pixel detector has been custom designed to withstand the irradiation

Also the sensor gets damaged by irradiation

How does radiation damage the sensor ?



Let's play a very strange version of football

There are 200 defenders on the field, one every 5 yards in each direction, on a regular grid

The defenders cannot move

The running back starts at a random position on his goal line and has to reach the opposite goal line

The running back can only run straight

If the running back hits the defender, game over

How often does the running back score a touchdown ?

- It depends on the starting position on the goal line'
- For some position the running back always scores
- For others he never scores

How does radiation damage the sensor ?

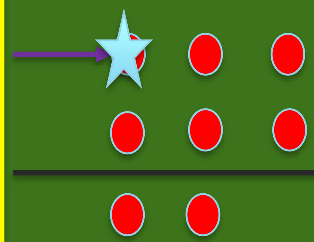
Now assume that in a running-back / defender collision the defender can be displaced from his original position

The probability that the running back will be able to reach the other end of the field will decrease with time

At a certain point the running back will no longer be able to score a touchdown

One way to minimize radiation damage is to keep the sensors cold (below 10 ^{o}F), this is equivalent to the defenders not being able to move if they are frozen in their initial position.

How does radiation damage the electronics ?



A similar thing happens inside the electronics

Our circuits are designed in 250 nm technology (most modern Intel CPUs are at the 15 nm level)

Special designs are used for the elements of integrated circuits to minimize the changes in response after irradiation

So, you cannot order it on Amazon…

The entire pixel detector is custom made by a team of scientists and engineers

- Design the sensor and have it fabricated by a specialized company (SINTEF, Norway)
- Design the chips and have them fabricated by a specialized company (IBM/ Global Foundries, VT)
- Assemble the chips and the sensors together using another specialized company (RTI/Micross, NC)
- Add a printed circuit board to make modules (University of Nebraska and Purdue University)
- Test the modules (University of Kansas, University of Illinois Chicago, Fermilab)
- 672 good modules are needed for the final detector, make (many) more

The sensor (i)

This is a very expensive piece of silicon

Start from sand

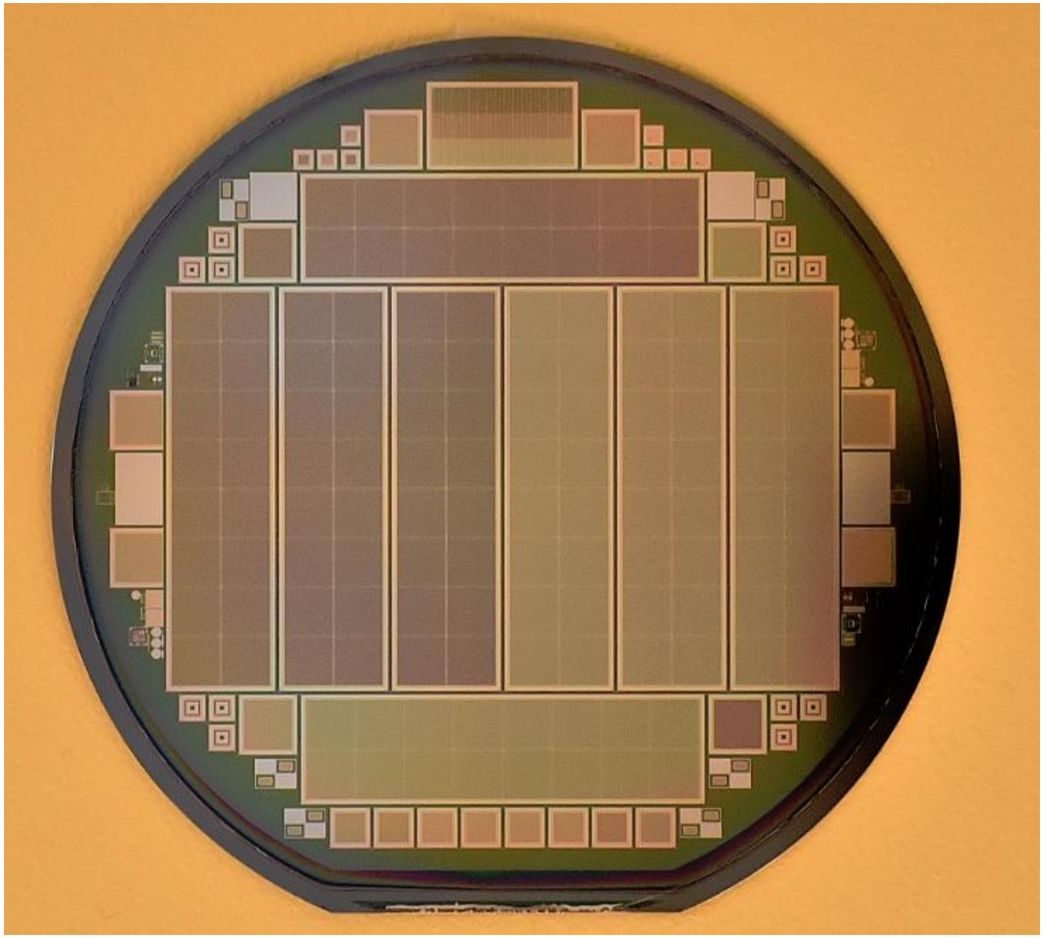
Create a silicon ingot

Slice it thin (1/85th of an inch)

Use photolithography and ion implantation to create tiny electrodes (100x150 µm)

8 sensors per wafer, cost per wafer about $6,000

Each wafer has to be sliced to extract the 8 sensors



The sensor (ii)

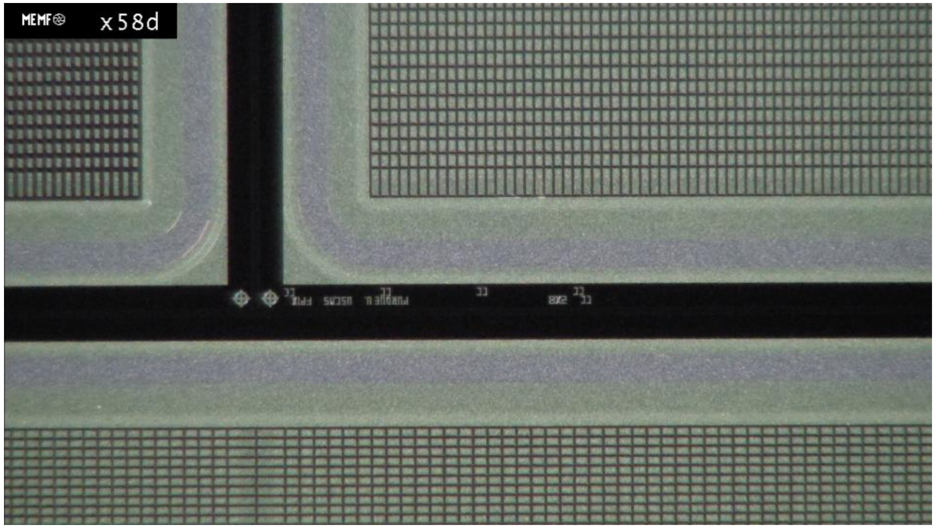
The fabrication process is much like etching

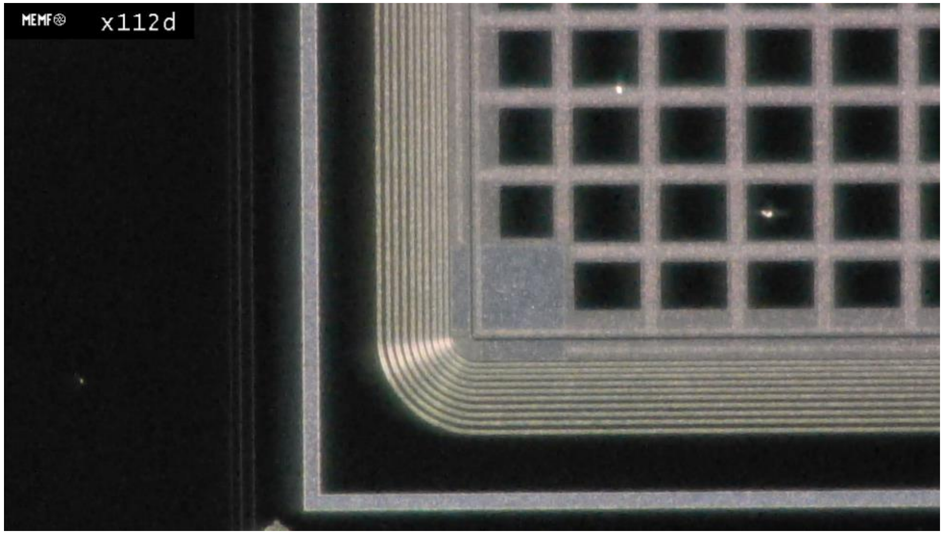
Except that the details have a size of 1 µm

And instead of depositing ink we deposit ions or aluminum

The base of the wafer is a silicon crystal

We then add ions (nitrogen, phosphorus) to create the electrodes, that are then plated with aluminum





The readout chip

The idea is the same

Start from a silicon wafer

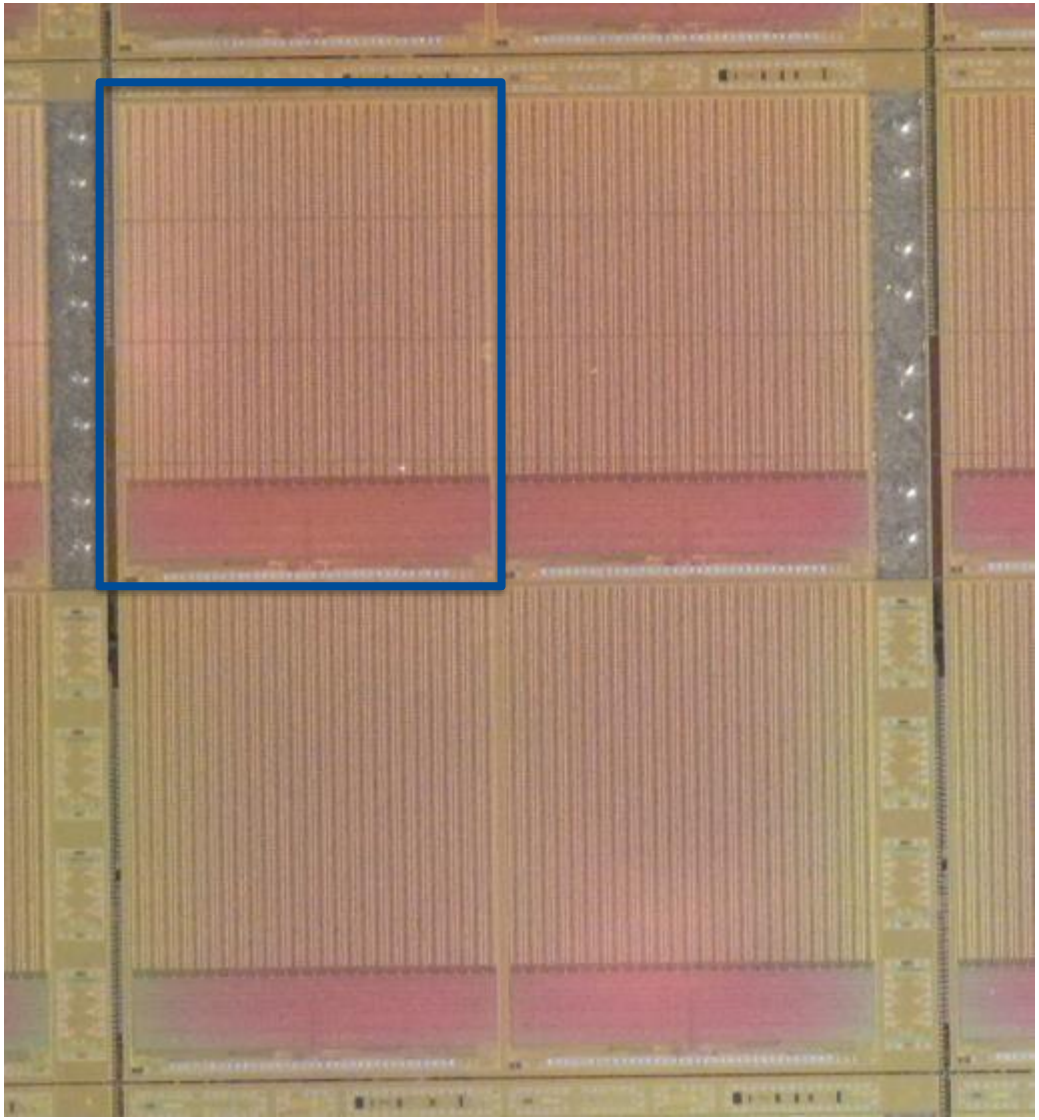
Deposit layers (9) of metal and insulator to create transistors

The feature size is ¼ µm

Each pixel cell (100x150 µm) has an amplifier, memory, control logic, calibration circuits

A very complex object

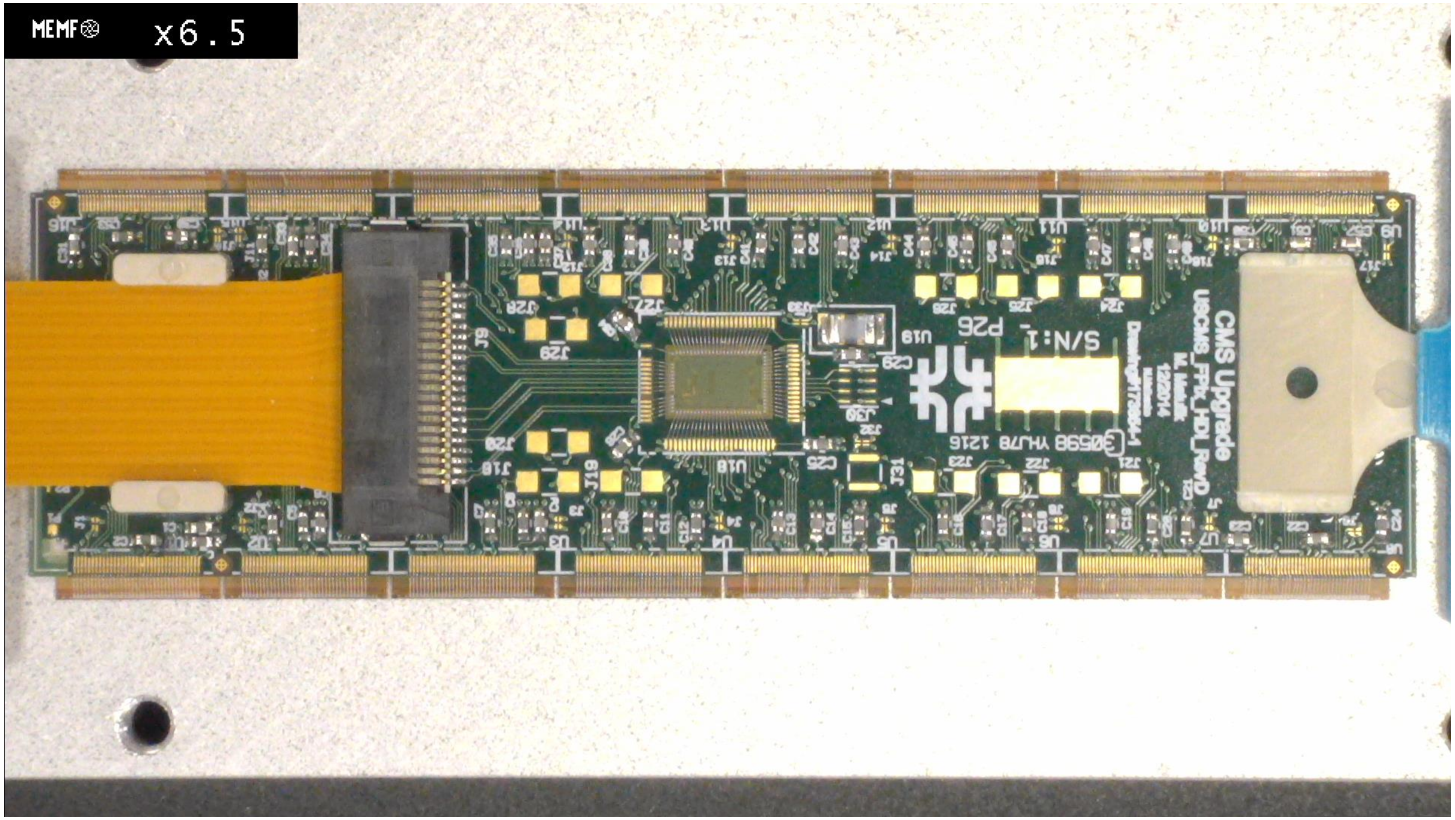
~95 wafers, each with 244 chips, tested individually



The module (i)

A module is made of 1 sensor, 16 readout chips, one flexible circuit (with an additional chip on top)

672 good modules required to assemble the detector



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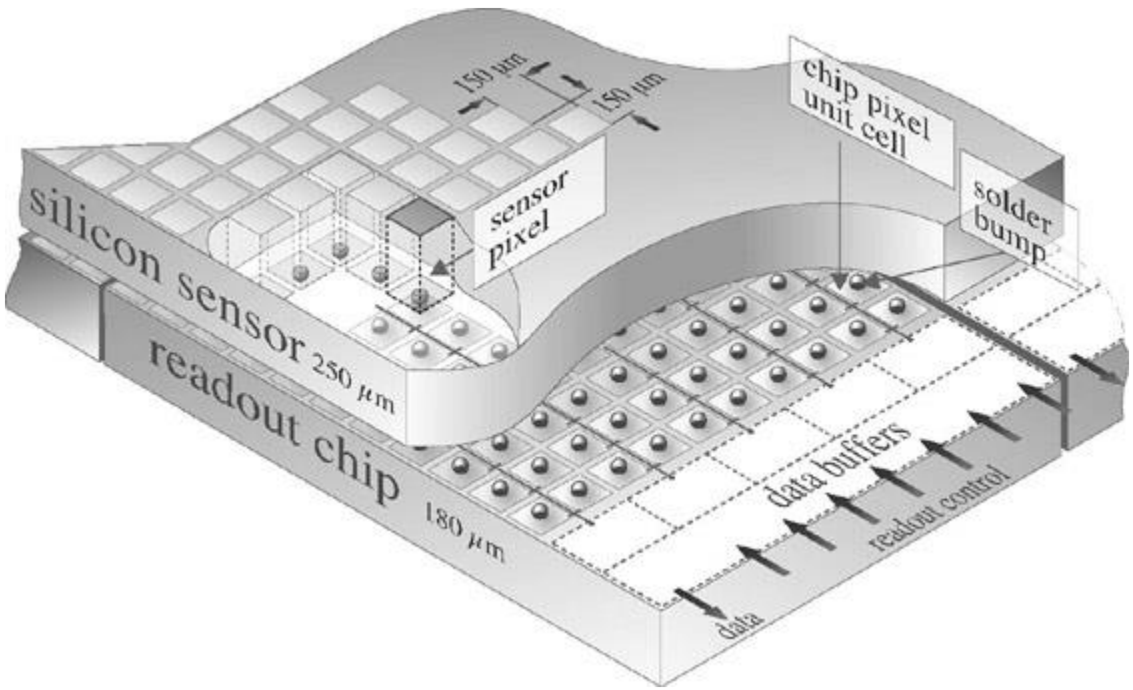
How do you put this together ? (i)

We need to make 4160*16 connections between each pixel of the sensor and the corresponding channel in the readout chips

Place a small solder ball (50 µm diameter) on each channel of the readout chip, put the readout chip on top of the sensor

Cook everything at 250 ^{o}F for 5 minutes



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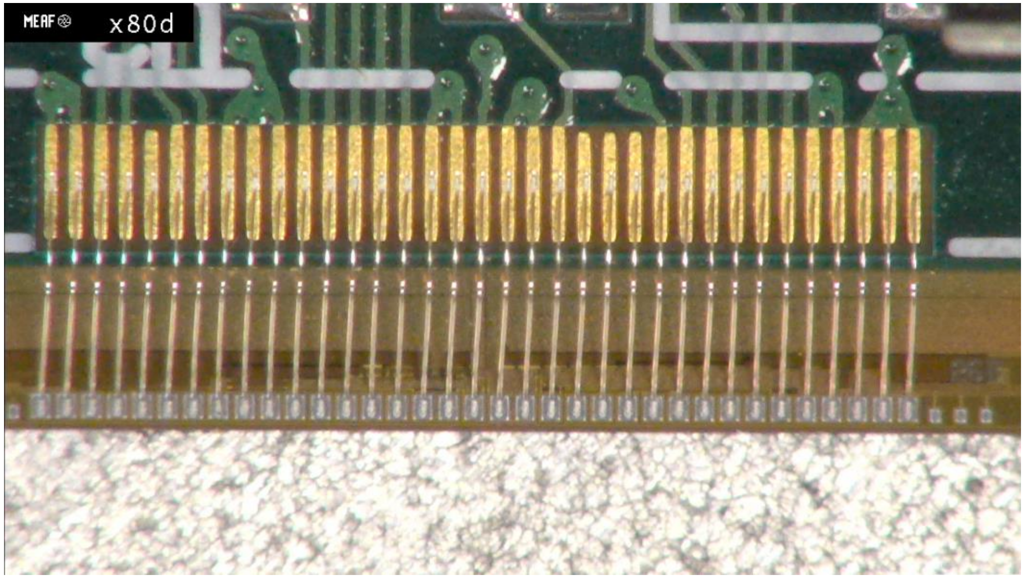
How do you put this together ? (ii)

Each readout chip needs power, control and trigger signal, addresses, connections for the readout, ground

Need about 35 connections per readout chip

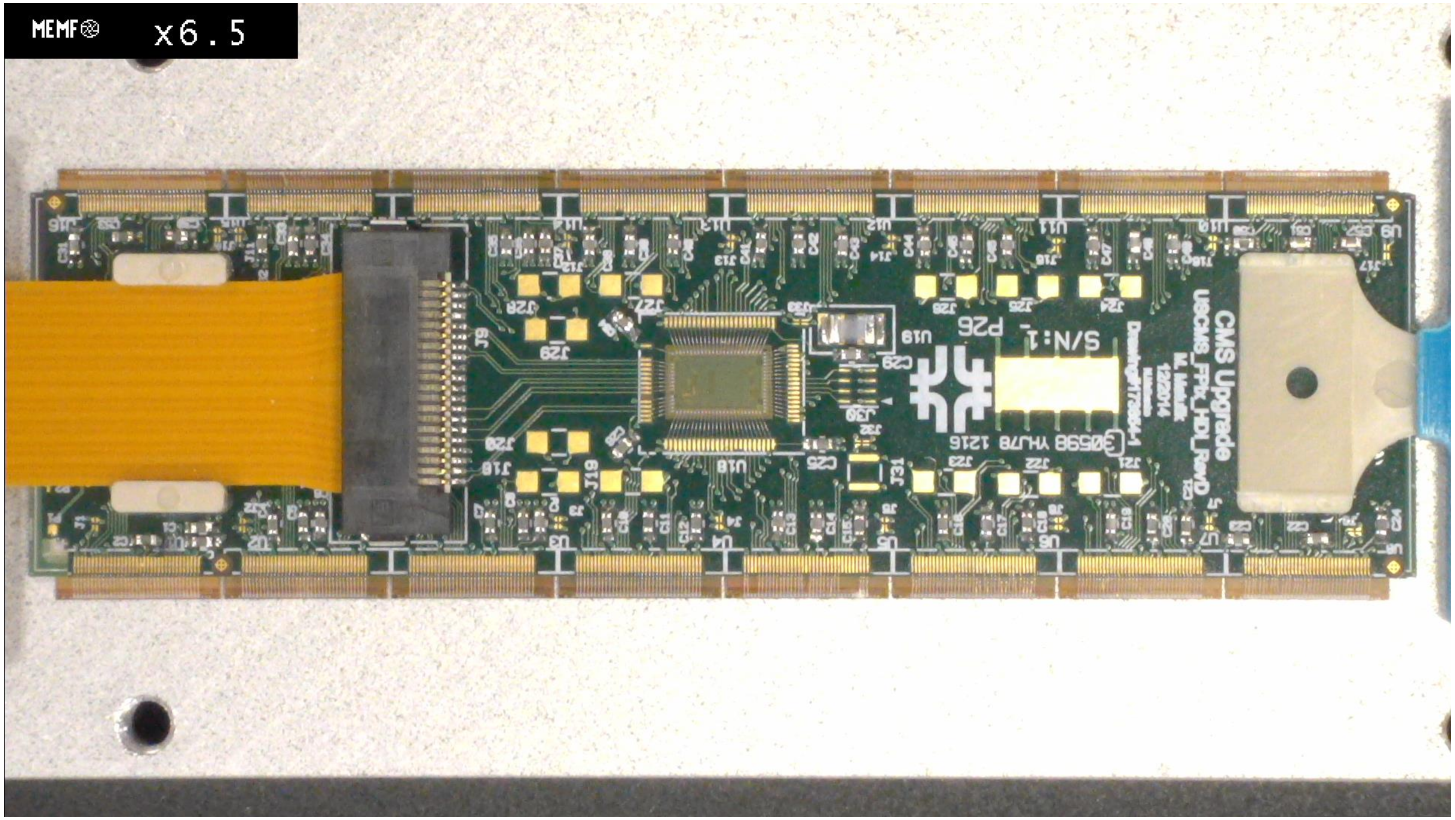
Put a flexible circuit on top of the sensor plus readout chip assembly, make the ~500 connections

Each connection is made with a 35 um wire, 3mm long, connected at both ends (flexible circuit, readout chip)



The module (ii)

There is an additional chip to orchestrate the traffic of data from the 16 readout chips, only 1 cable to send the data out



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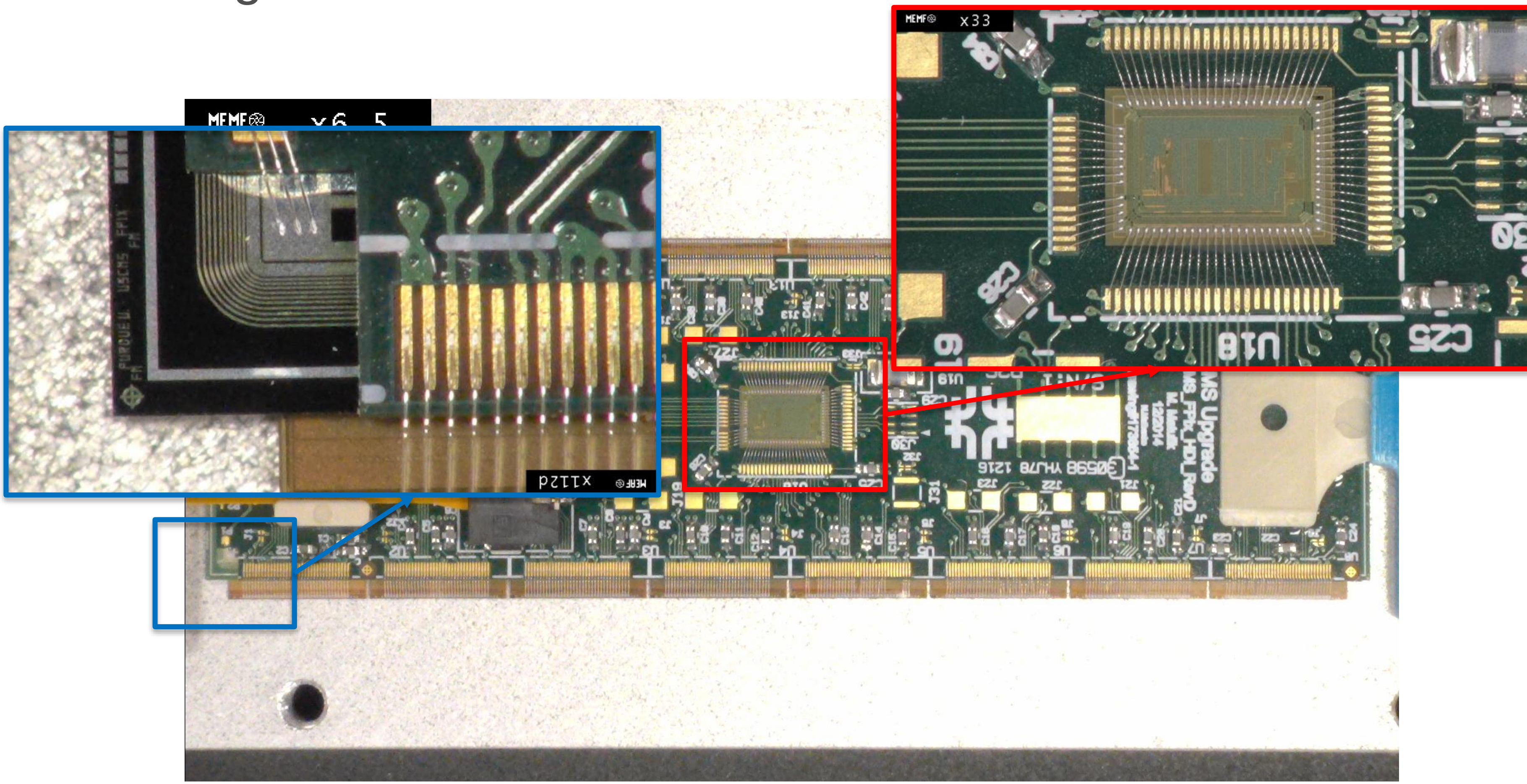
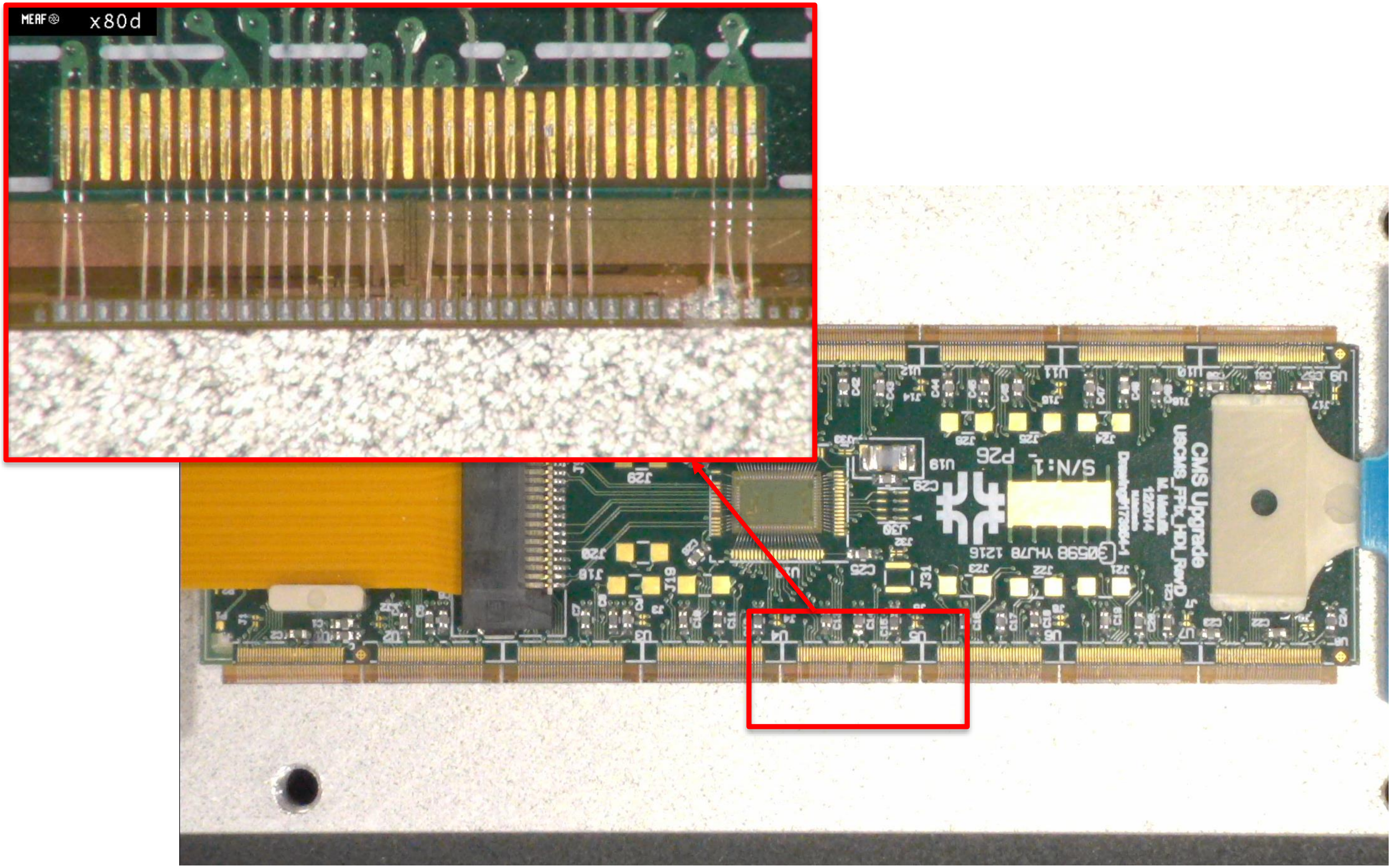
The module (iii)

There is an additional chip to orchestrate the traffic of data from the 16 readout chips, only 1 cable to send the data out, and a bias voltage connection for the sensor

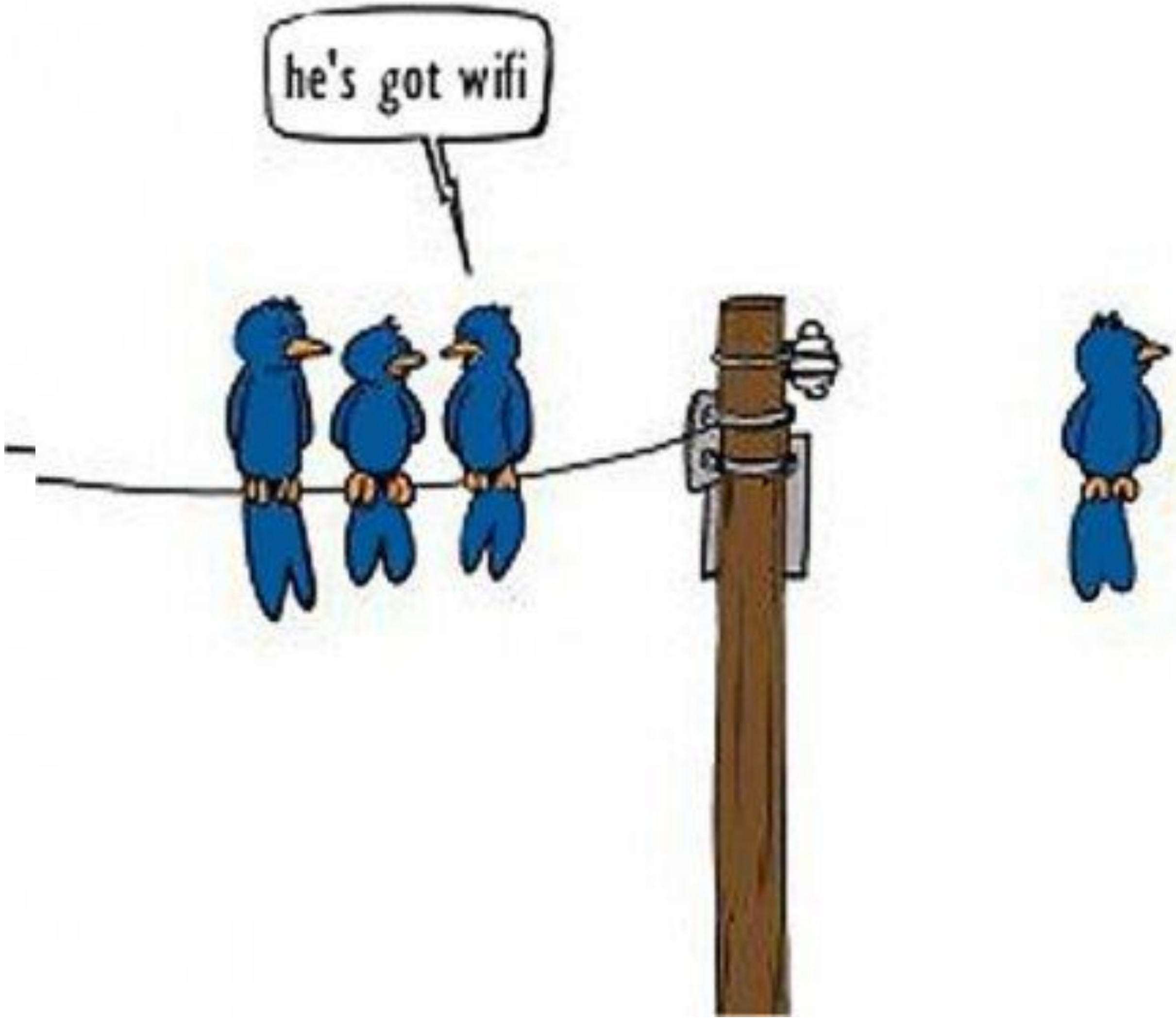


The module (iv)

And sometimes things don't work and have to be fixed….



And then you have to support all of this



Mechanical supports

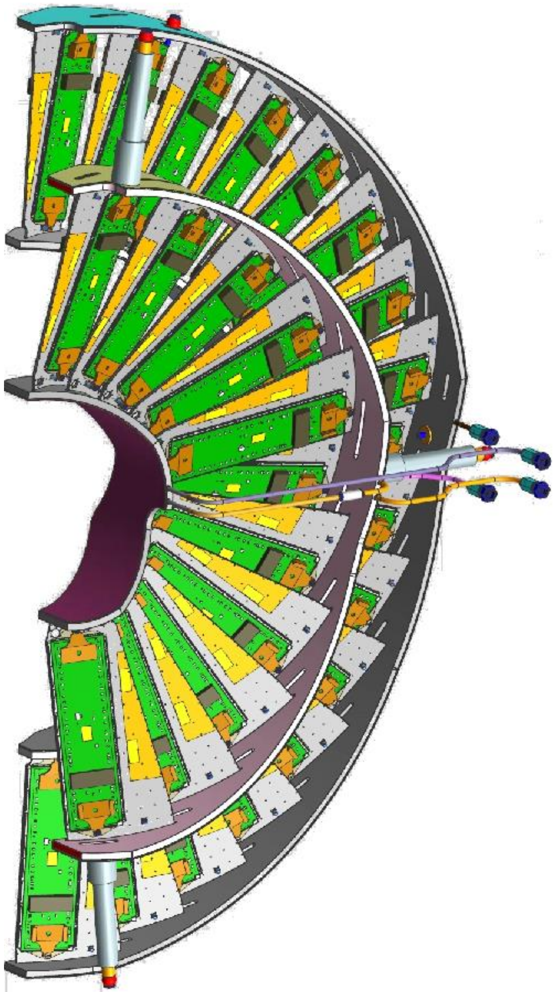
The 672 modules are mounted on 24 half disks (2 sizes, with 34 or 22 modules each)

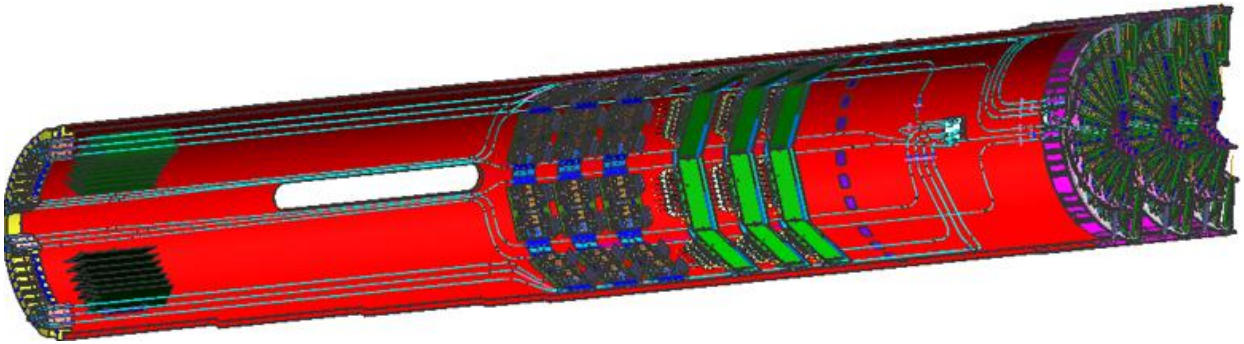
Six disks (3 outer disks + 3 inner disks) are mounted on a half cylinder support

Two half cylinders are mounted on each size (+Z or –Z detector end) to surround completely the CMS interaction point

This allows for detector insertion with the beam pipe already in place

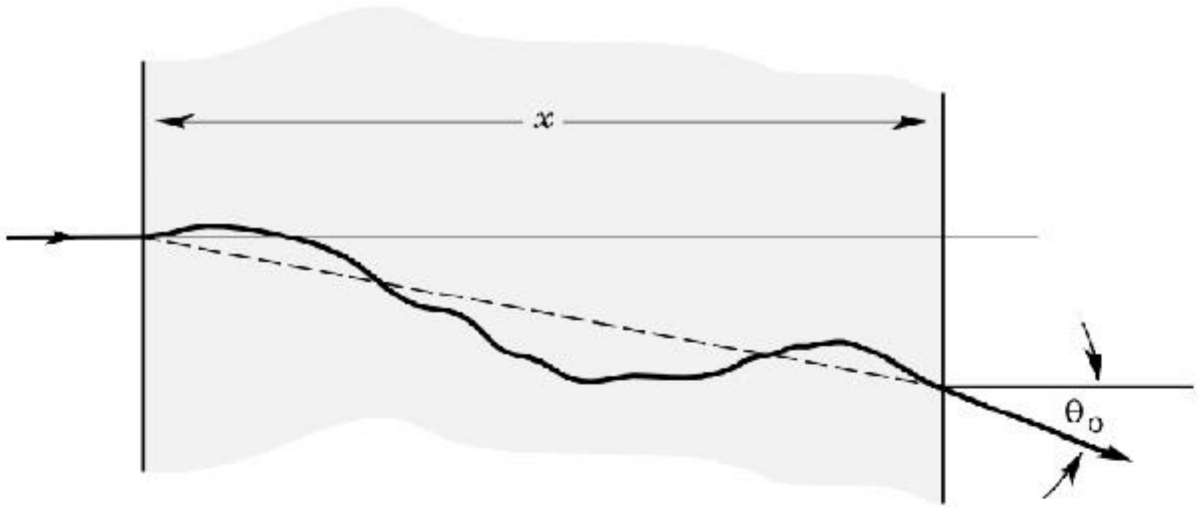
All the supports are made of carbon fiber





Why Carbon Fiber ?

Back to the football analogy ? As a running back, would you rather have a defense made of 3 year old kids weighting 30 pounds, or a real NFL defense ? Suppose you don't have any offensive line……



If the material particles have to go through is light, then they get deflected less

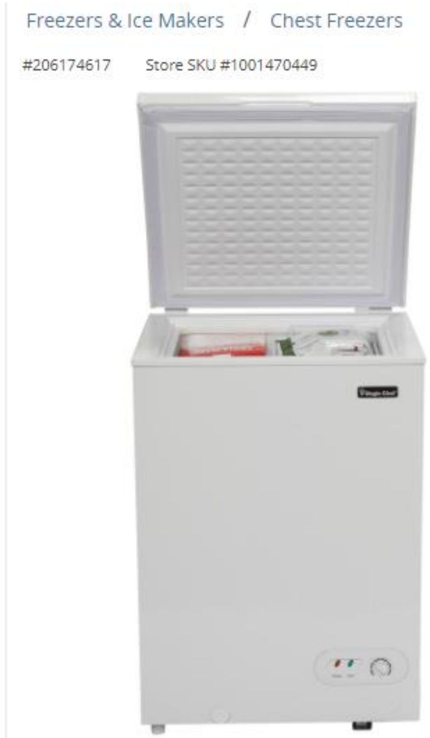
We need to extrapolate back the trajectories to the point where the particle was created

Keep it cold

To minimize the radiation damage, we need to keep the detector cold (below 10 ^{o}F)

The electronic components generate a few kW of heating (it's really a space heater)

Putting a space heater inside a freezer is not a really smart idea, you just waste electricity



How to make ice cream

Ice + Rock salt

The salt melts the ice, this transformation requires heat, which is taken away from the milk (plus other stuff) in the canister

The milk freezes and transforms into ice cream…

We do the same thing, except that we use CO_2 under high pressure. Some of the CO_2 is in liquid phase, other is in gaseous phase. The CO_2 boils taking away the heat from the detector.

Very efficient requires very small diameter cooling tubes (few mm)

Putting all together

Install all the modules on the mechanical supports, do all the electrical / optical / cooling line connections

Test, and fix problems

Transport to Geneva (Switzerland), reassemble, test again

Install in the detector

Start taking data

All of this happened between June 2016 and March 2017

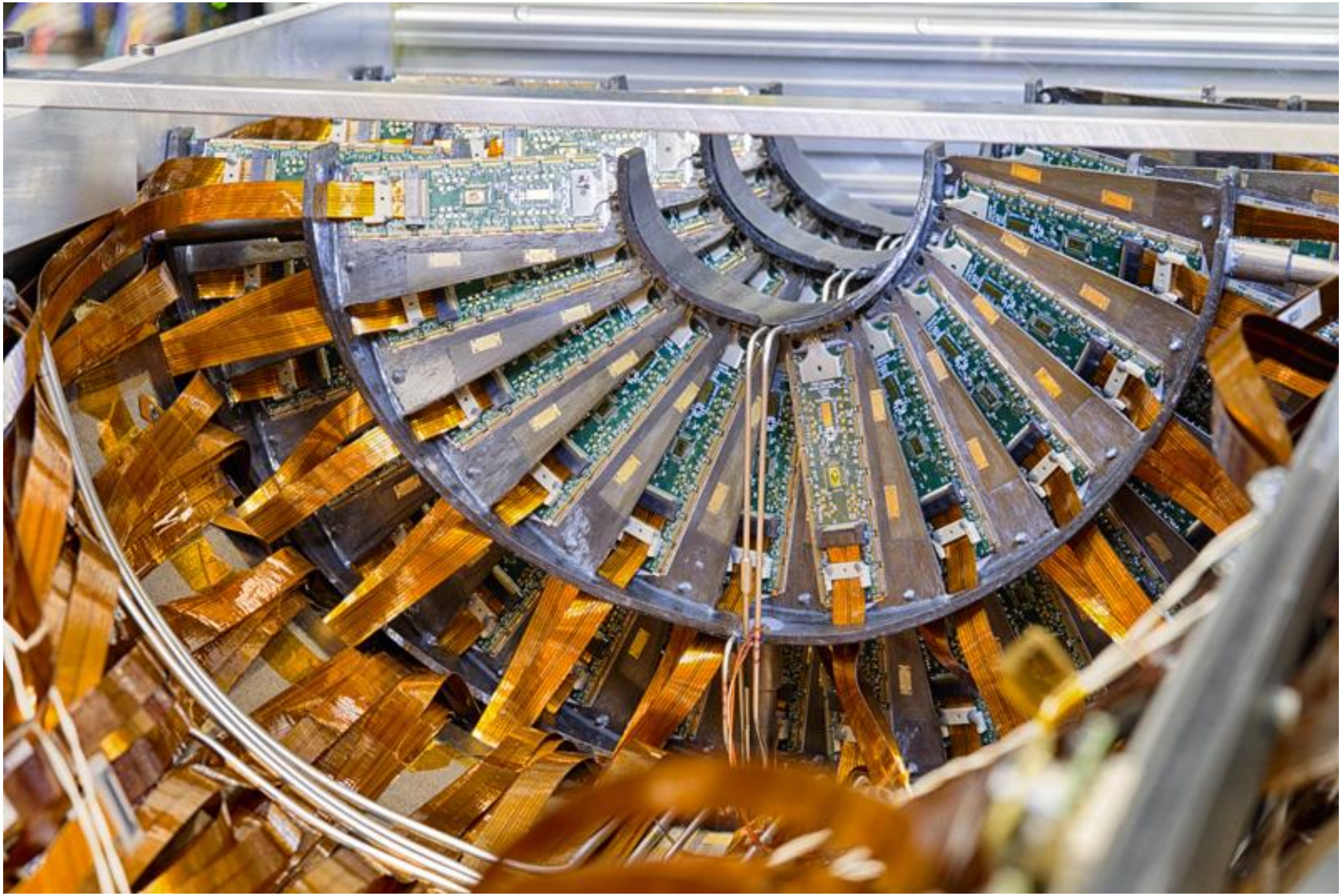
Installing disks inside the half cylinder

We did this work three times
First at Fermilab (then removed the disks for transport to CERN)
Then at CERN
Then a 2nd time at CERN because we found a problem and had to inspect / replace some of the flexible cables

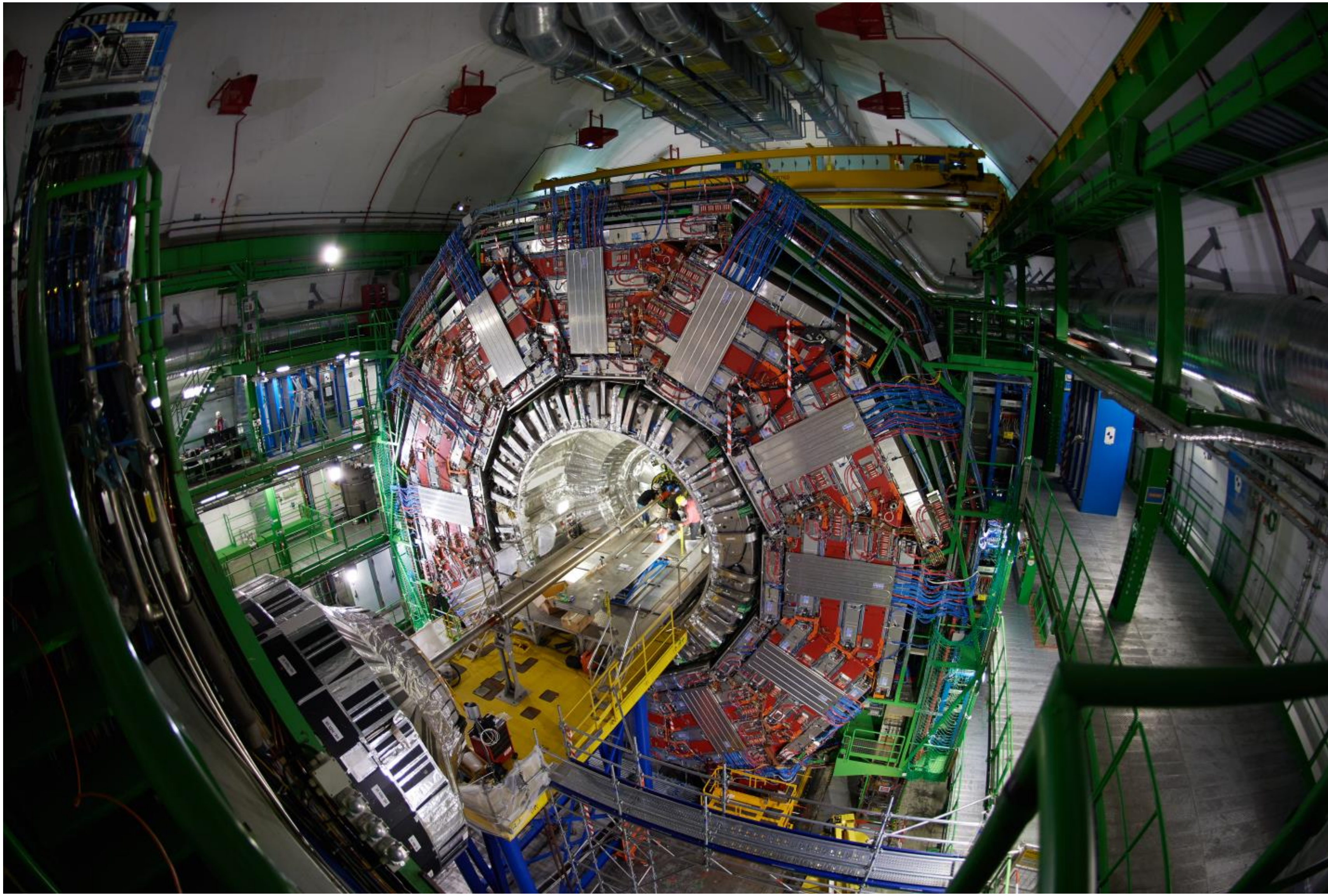
Installation

Installation

Installation



Insertion



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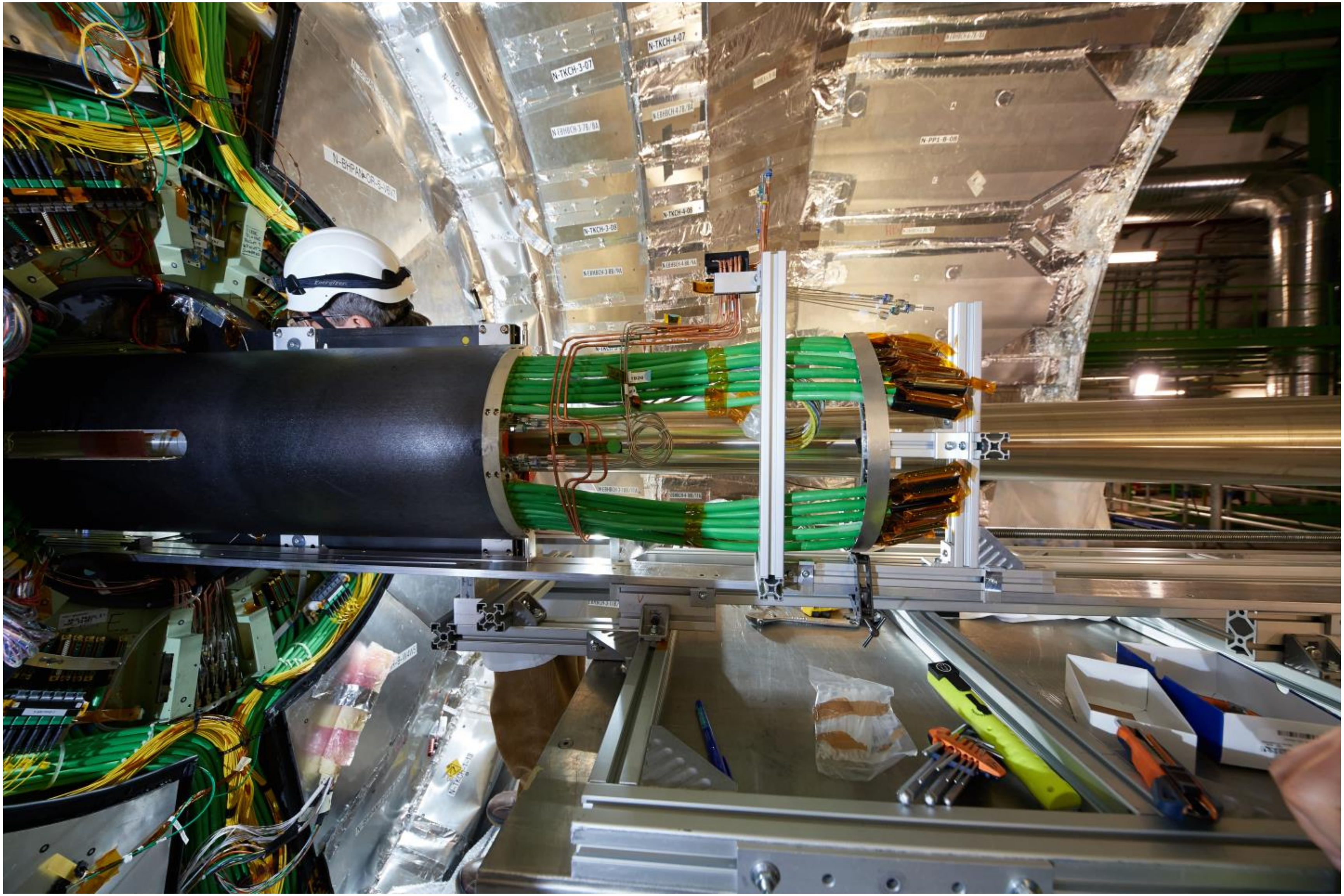
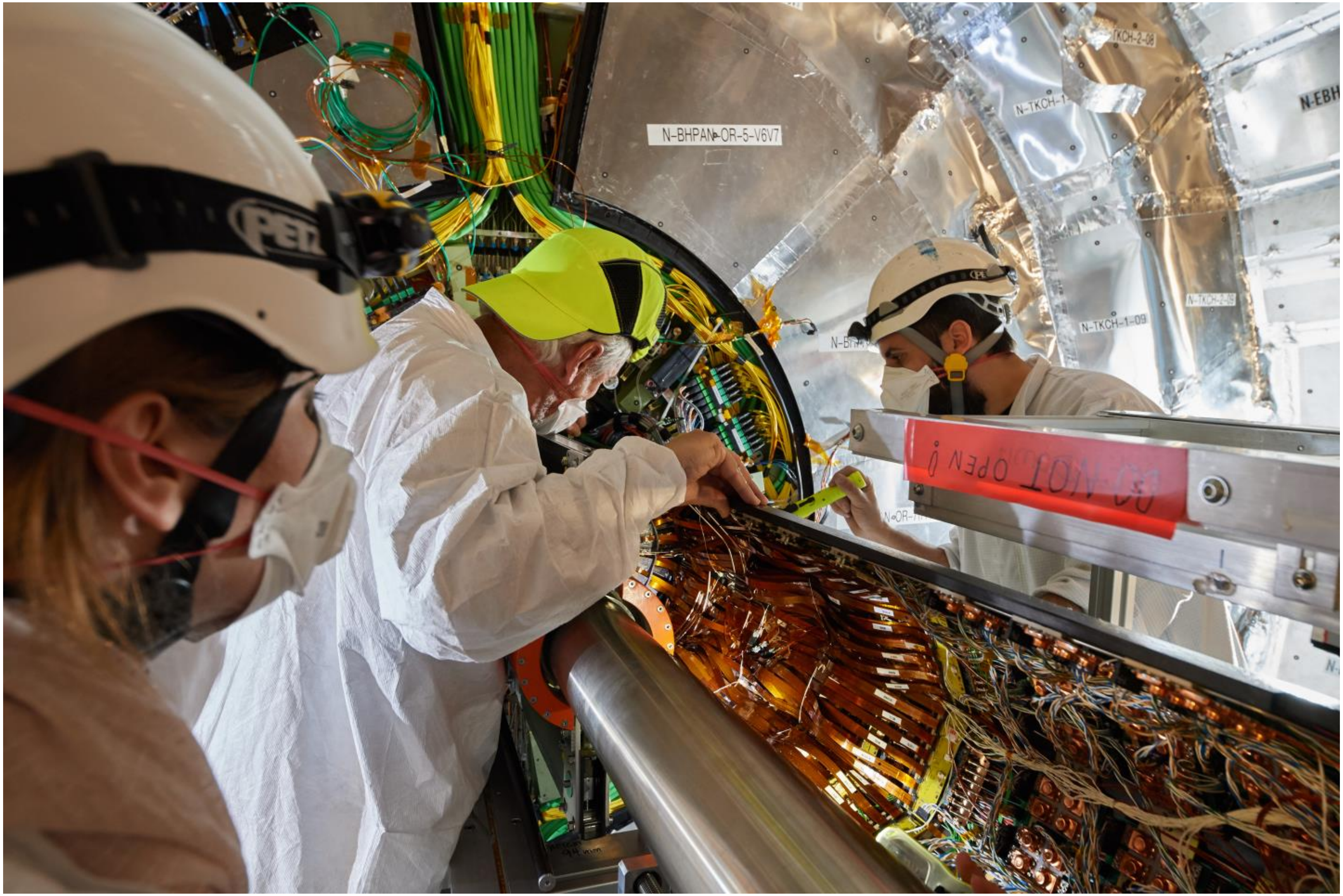
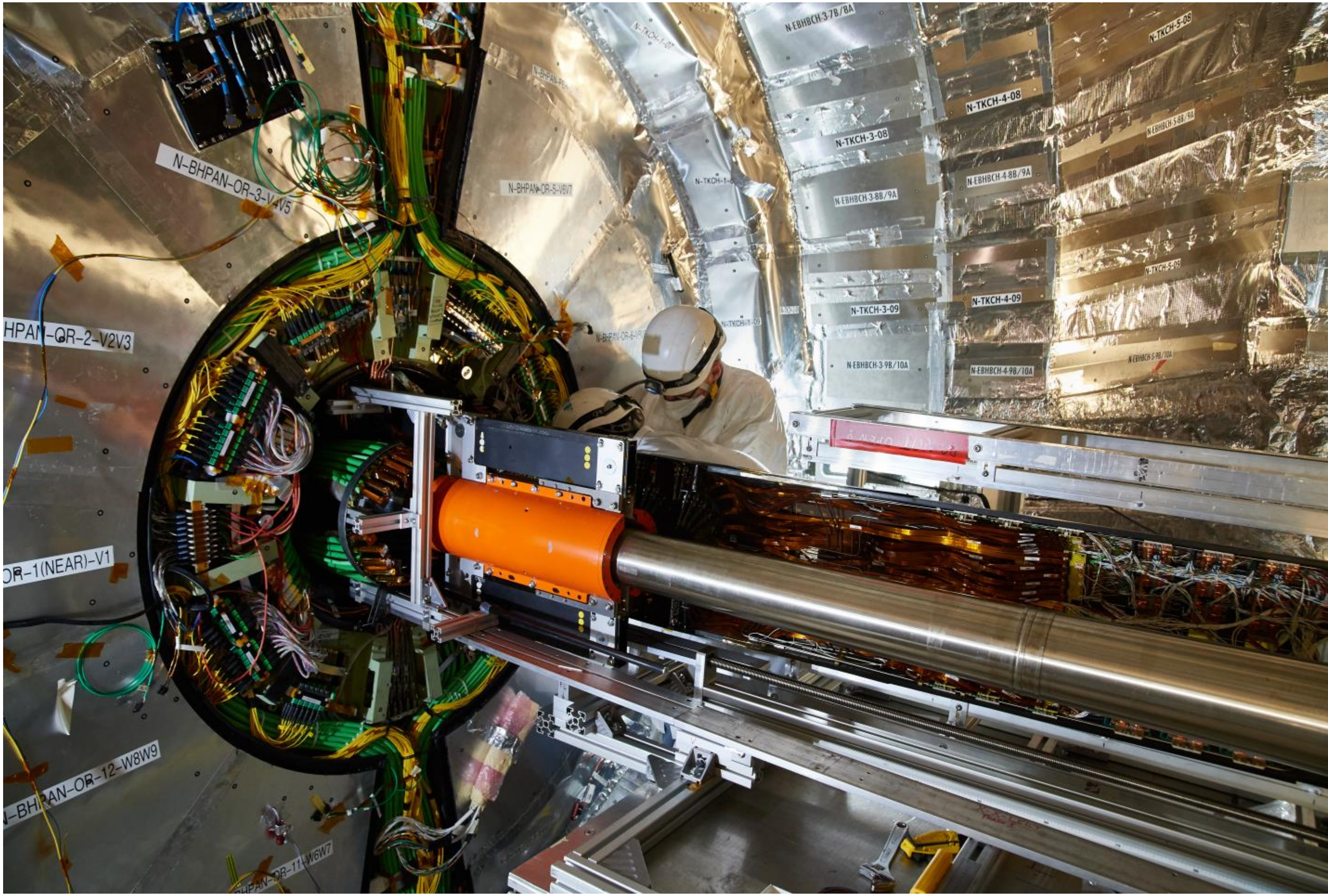


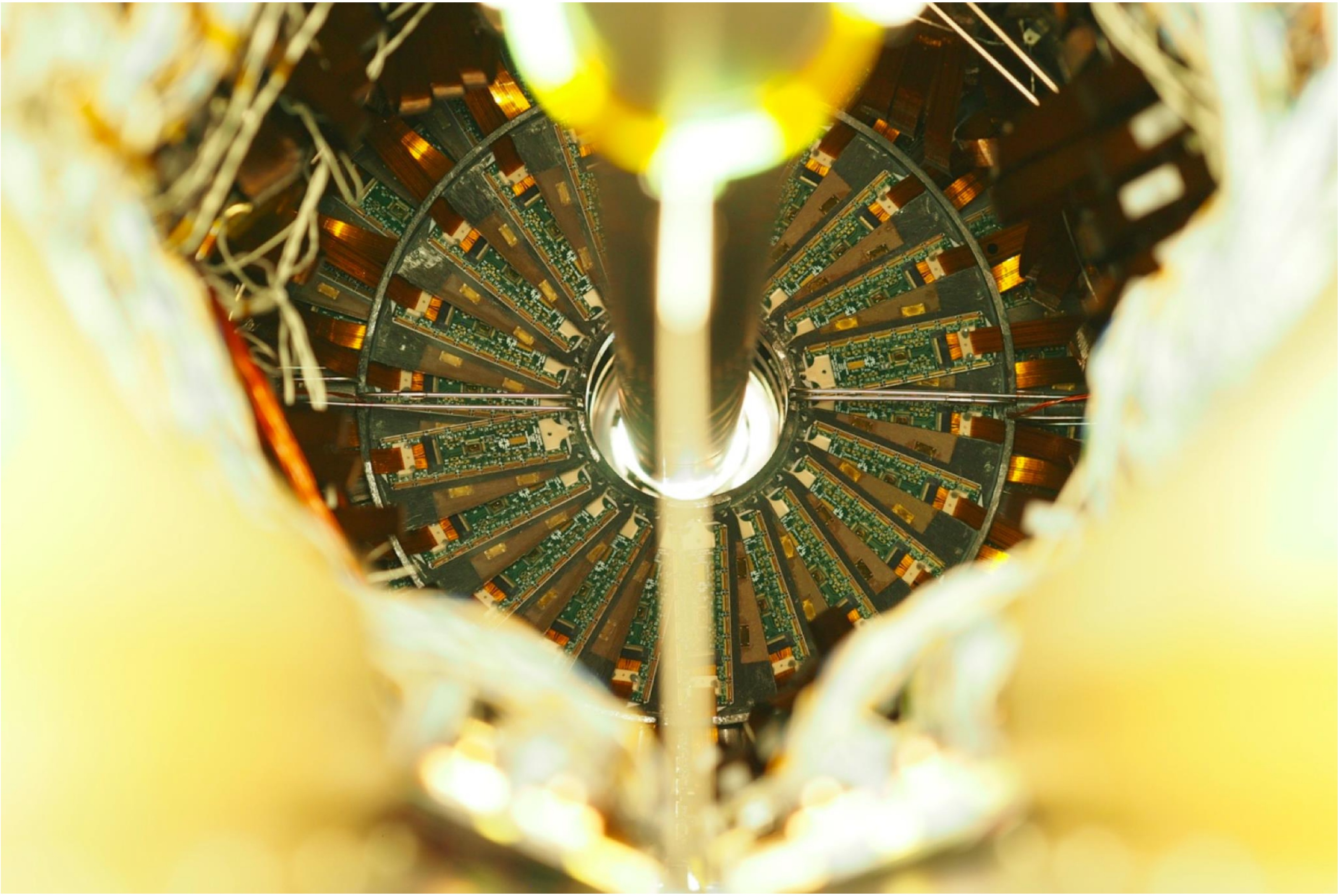
Insertion



Insertion


N-BHPAN-OR-3-V4V5
HPAN-OR-2-V2V3
OR-1(NEAR)-V1
N-TKCH-3-08
N-TKCH-4-08
N-TKCH-3-09
N-TKCH-4-09
N-TKCH-5-08
N-EBHBCH-3-8B/9A
N-EBHBCH-4-8B/9A
N-EBHBCH-3-9B/10A
N-EBHBCH-4-9B/10A

The detector installed inside CMS



It was a success

There were a lot of problems during the construction

- Problems with the bump bonding company
- Problems with the flexible circuit

  We are asking industry to do very difficult things
- Problems with welding the cooling lines

  We were not fully prepared
- Problems with the aluminum flexible cables

  Not the smartest design idea, too fragile

We ended up with >95% of the channels working

Dead channels caused by loose connection of a control signal plus broken aluminum flexible cables

We were able to take data efficiently in 2017

It was a success

Great team work

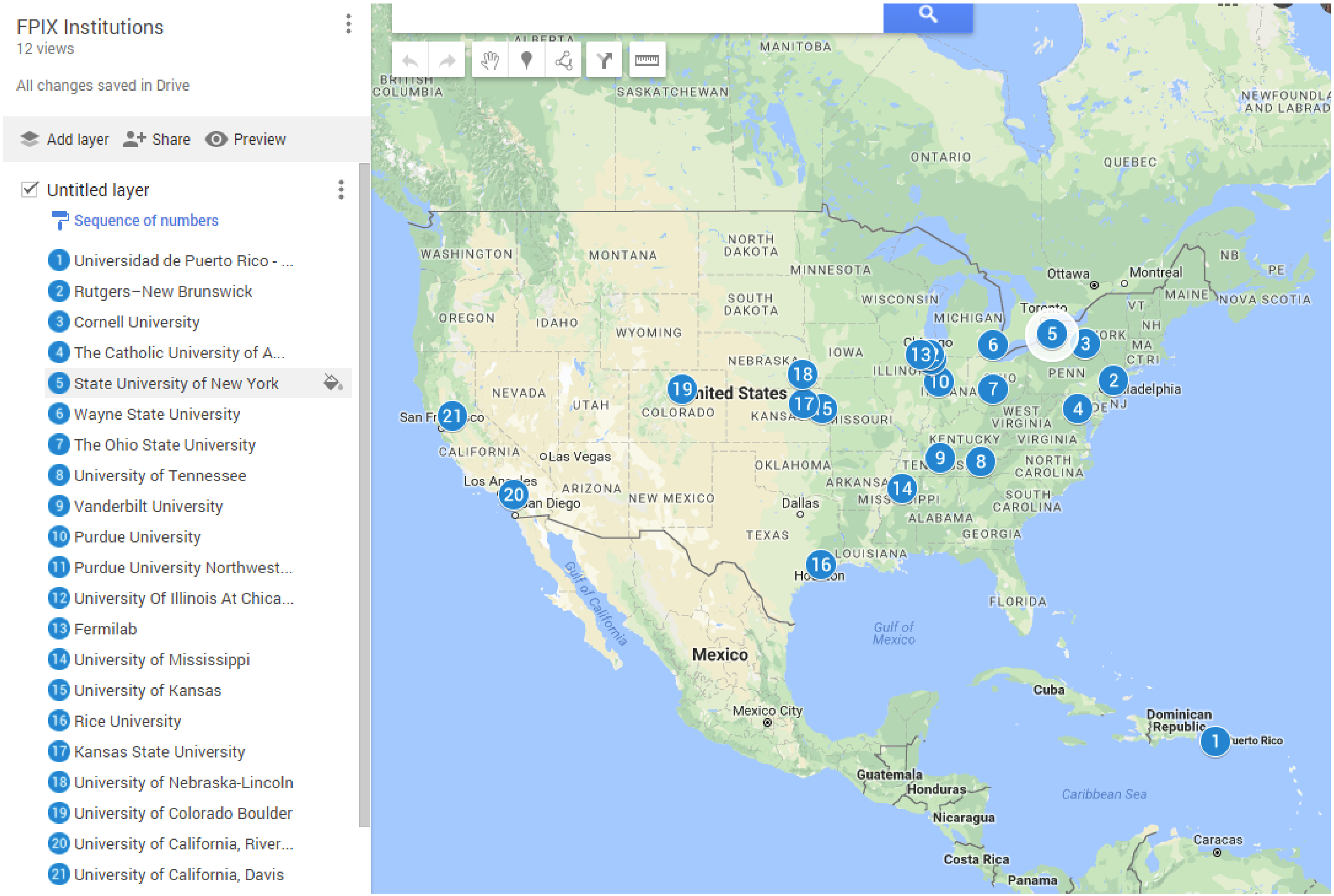
- Engineers and technicians from Fermilab and other institutions
- Scientific personnel (Fermilab scientists and postdocs, university professors, graduate and undergraduate students, engineers)

Partially based on expertise from construction of original detector

It was a technical and scientific challenge (and at times a quite stressful experience)

The reward is the science that can be made with this new instrument

Collaborators

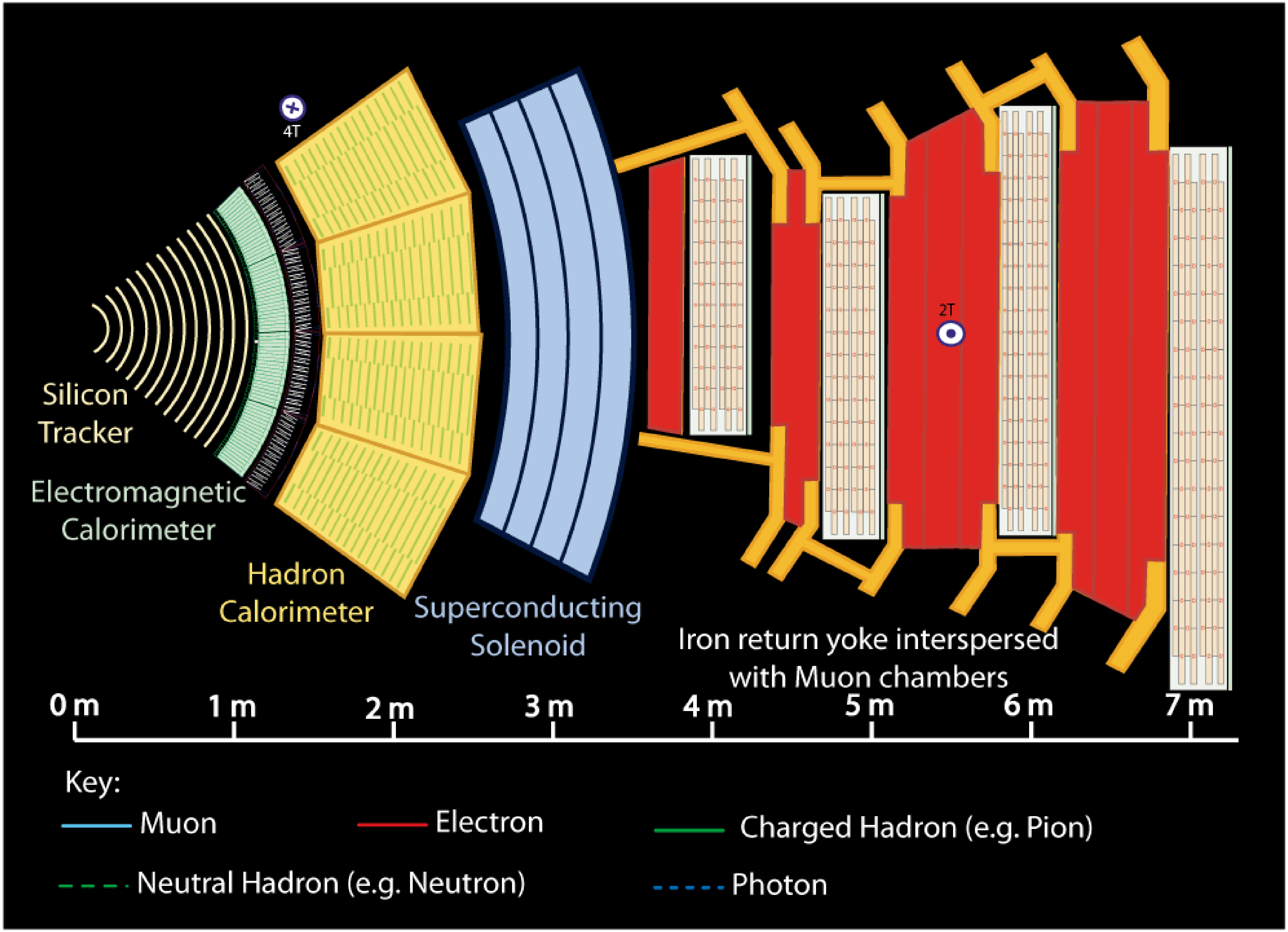


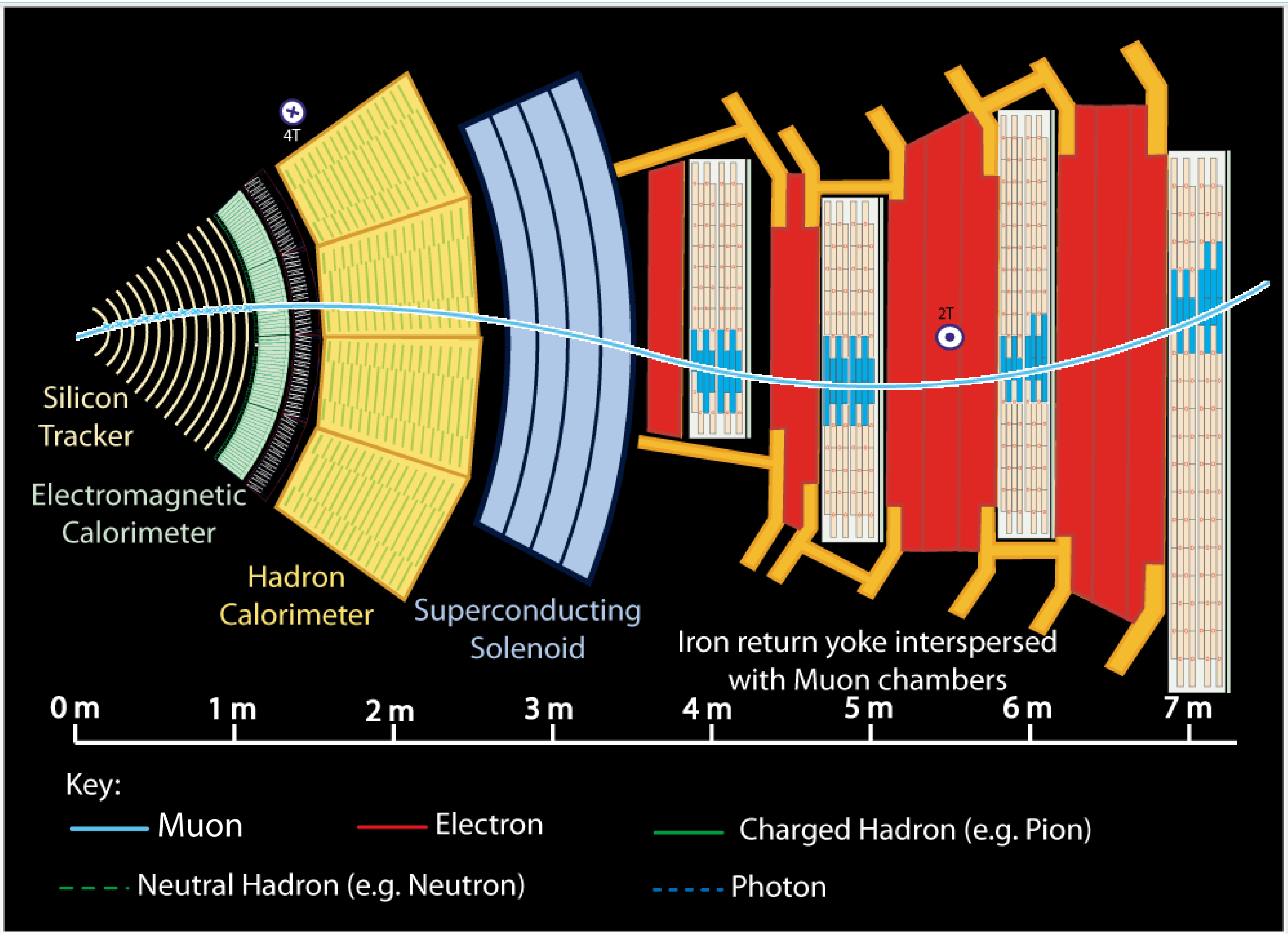
It is not over …..

We have found a serious problem in a component of the detector which if not solved would force us to turn off almost the entire pixel detector during 2018

We have extracted the pixel detector (half of it so far, next half comes out in 10 days) and we are replacing the faulty component

Probably this operation will have to be repeated next year (we hope that by then we will have a real solution for the problem)


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



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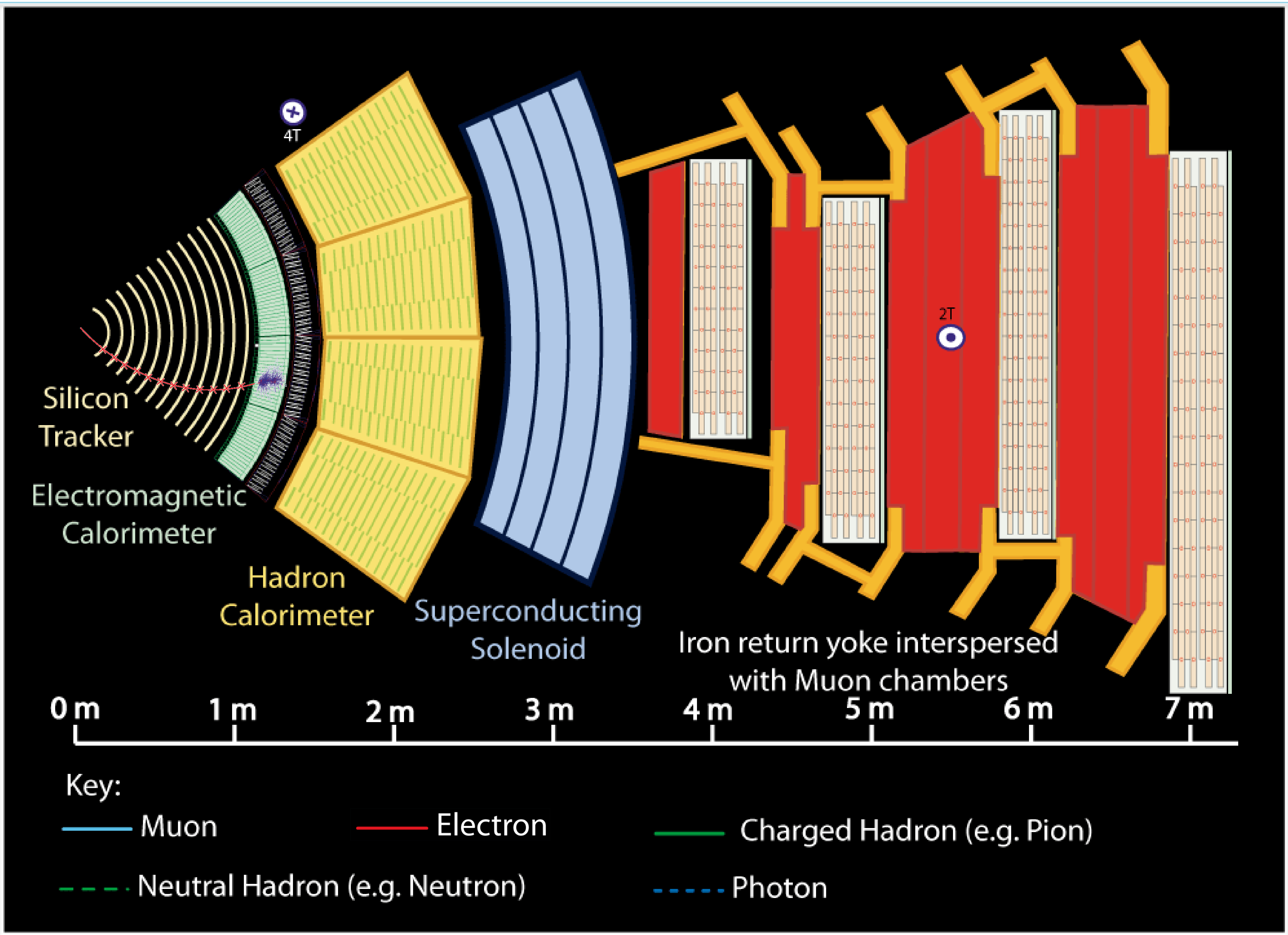

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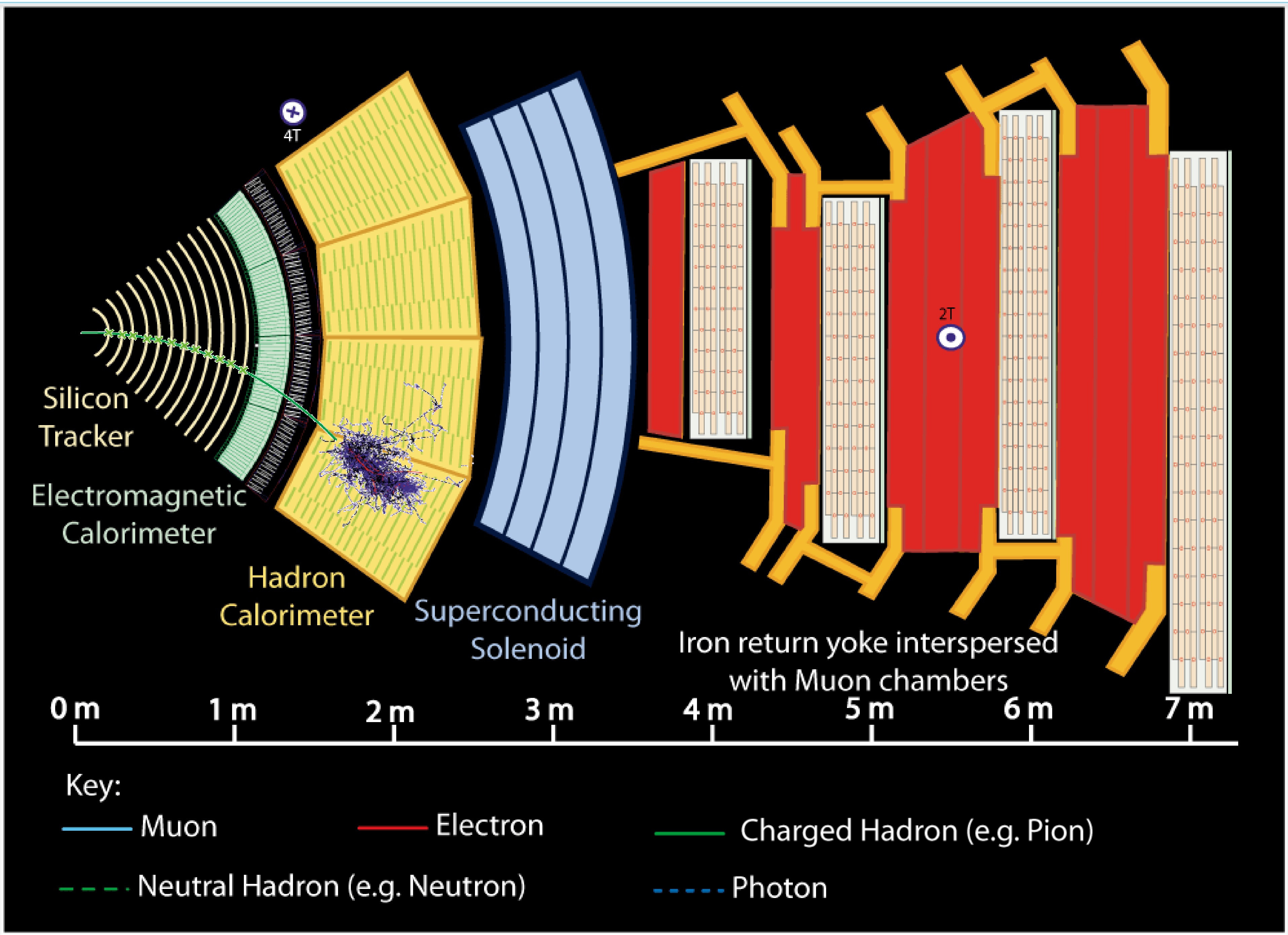
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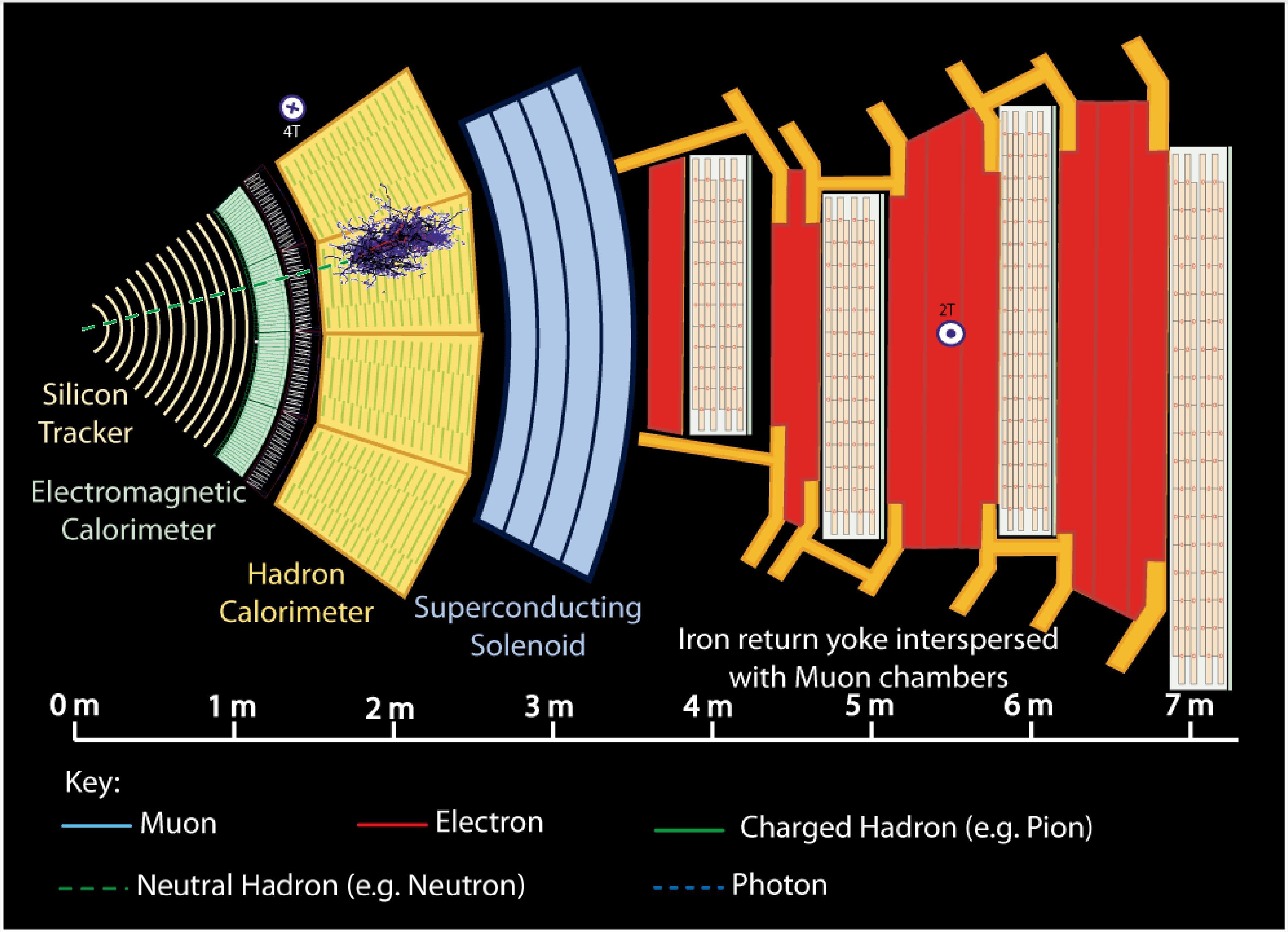

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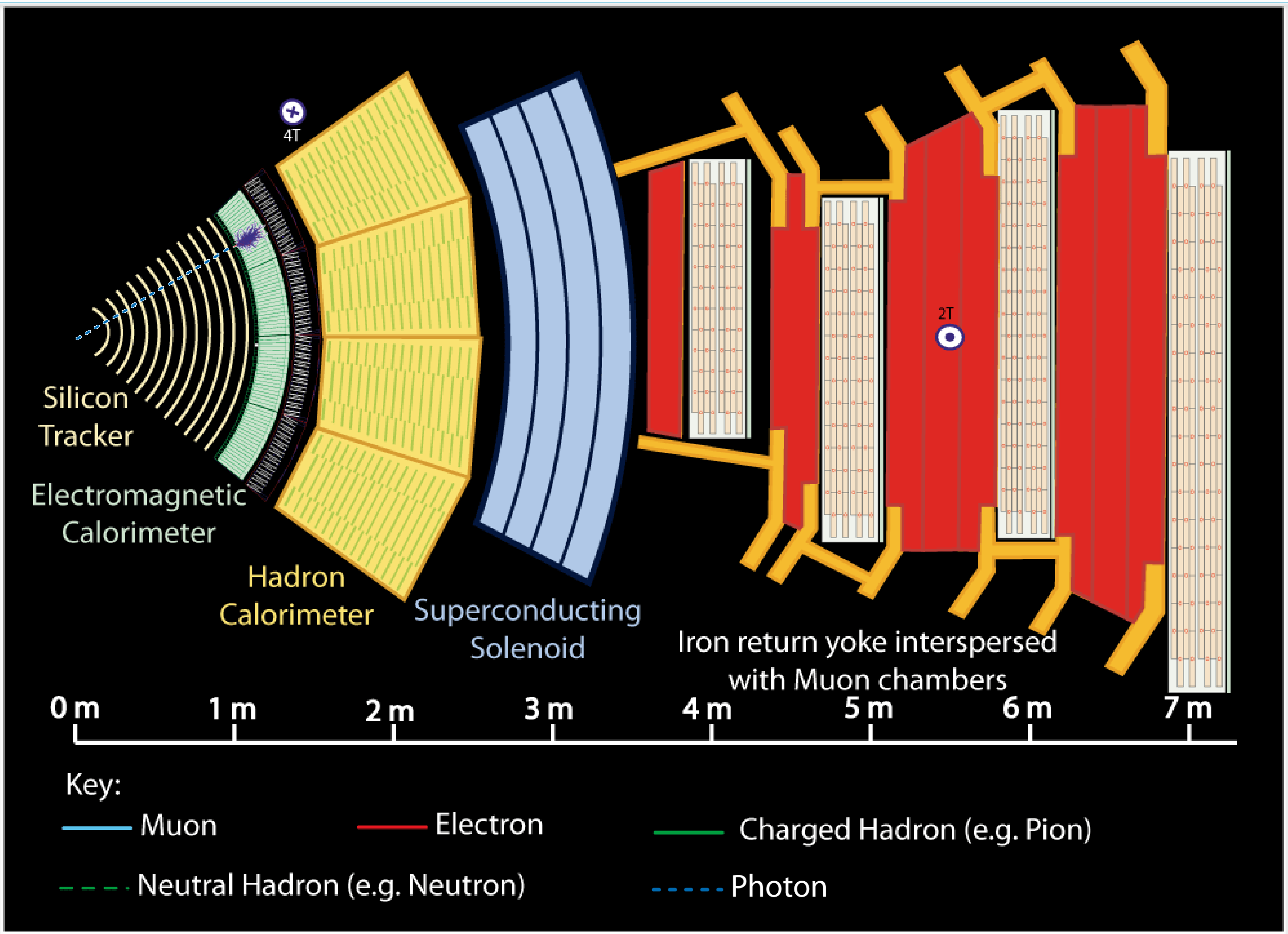
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